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INVESTIGATION OF PORTLAND BLAST-FURNACE SLAG CEMENTS

Report 2

SUPPLEMENTARY DATA

by

Bryant Mather

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FOREWORD

The investigation of portland blast-furnace slag cements authorized on 12 May 1955 by the Office, Chief of Engineers, and carried out by the Concrete Division of the USAE Waterways Experiment Station, had yielded results early in 1956 that appeared sufficiently conclusive to merit consideration being given to the possibility of taking action thereon. Accordingly, they were summarized and reviewed at a conference in May 1956 and, with the addition of certain data developed later, published in December 1956 as Technical Report 6-445. As was indicated in Technical Report 6-445, some phases of the original program were incomplete and a supplementary program was almost wholly incomplete. Since the preparation of TR 6-445, additional data have been developed as the original program has been continued, and certain of the previous results have been reanalyzed. This report presents and discusses these additional data.

This investigation was carried on through fiscal year 1963 as a part of item CW 601 "Research in Mass Concrete" of the Civil Works Investigation Program of the Corps of Engineers. Since that date the work has been a part of item CW 614, now item ES 614, "Research on Properties of Cementitious Materials," of the Engineering Studies Program of the Corps of Engineers. Two other investigations, conducted by the Ohio River Division Laboratories and the Missouri River Division Laboratory of the Corps of Engineers, are also summarized herein as Appendixes A and B.

The work at the Concrete Division of the Waterways Experiment Station was under the general direction of Mr. Thomas B. Kennedy. This report was prepared by Mr. Bryant Mather. Directors of the Waterways Experiment

Station during the course of this work were Col. Andrew P. Rollins, Jr., CE, Col. Edmund H. Lang, CE, Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE; Mr. J. B. Tiffany was Technical Director.

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SUMMARY

During the review of the first report of this series, additional questions relating to the performance of portland blast-furnace slag cements were raised. These concerned in particular the effects of interrupted or abbreviated moist-curing of portland blast-furnace slag cement concrete, and the effects of this cement on corrosion of reinforcing steel. Also, certain phases of the basic investigation were then incomplete, and during their completion additional questions were raised, particularly regarding sulfate resistance of portland blast-furnace slag cement concrete and resistance of such concrete to scaling when exposed to severe natural weathering. This report describes the studies made to answer these questions, and presents data from the studies that were incomplete at the time of publication of the first report. Summaries of investigations of portland blast-furnace slag cements made by the Ohio River Division Laboratories and the Missouri River Division Laboratory in connection with actual construction projects are included as Appendixes A and B.

From the study of the effects of continuation of moist-curing, for different lengths of time, no indications were found to suggest that concrete made with portland blast-furnace slag cements is more adversely affected by early termination of moist-curing than is concrete made with type II portland cement. This conclusion is based on tests at ages of from 7 days to 1 yr of concrete made with eight portland blast-furnace slag cements and one type II portland cement.

Tests for bond-to-steel indicated a similar relation of bond stress to slip at ages of both 28 and 90 days for the concrete made with the portland blast-furnace slag cements and the type II portland cement; similarly the relation between bond stress at both ages to produce a given slip showed a normal relation to the compressive strengths of these concretes at these ages.

No indications were found from the tests of corrosion of steel to suggest that embedded steel in concrete made with the two portland blast-furnace slag cements having the highest content of sulfide sulfur of all

the test cements suffered a greater degree of corrosion than did steel in concrete made with type II portland cement. The amount of corrosion observed at all ages in all exposures, including five years exposure to alternate immersion in warm sea water at St. Augustine, Florida, was significantly less on steel embedded in concrete made with both portland blast-furnace slag cements than on steel embedded in concrete made with the reference type II portland cement.

Exposure of concrete specimens made with portland blast-furnace slag cements, blends of a portland blast-furnace slag cement and a natural cement, and with type II portland cement to seven years of severe natural weathering at Treat Island, Maine, has caused only 5 of the 108 specimens to deteriorate to such an extent that their relative dynamic Young's moduli of elasticity are lower than at the time of installation. One of these represents concrete made with the 75:25 blend with natural cement; the other four are of concrete made with the 70:30 blend. However, all specimens suffered scaling on their top surfaces.

No basis was found for establishing different requirements for curing concrete made with portland blast-furnace slag cement from those applicable to concrete made with types I and II portland cement. No basis was found for restricting the use of portland blast-furnace slag cement in reinforced concrete construction or where exposed to severe natural weathering. Additional studies of the mechanism and factors involved in sulfate attack and the prevention of sulfate attack would be desirable for the purpose of establishing more clearly the applicability of the various physical and chemical procedures that have been employed to elucidate these phenomena.

INVESTIGATION OF PORTLAND-BLAST FURNACE SLAG CEMENTS

SUPPLEMENTARY DATA

PART I: INTRODUCTION

Purpose and Scope of Supplementary Tests

1. The first report of this series (published in December 1956) describes the basic investigation to which the tests reported herein are supplementary.

2. During the review of the first report, additional questions relating to the performance of portland blast-furnace slag cements were raised. These concerned in particular the effects of interrupted or abbreviated moist-curing of portland blast-furnace slag cement concrete, and the effects of this cement on corrosion of reinforcing steel. Also, certain phases of the basic investigation were then incomplete, and during their completion additional questions were raised, particularly regarding sulfate resistance of portland blast-furnace slag cement concrete and resistance of such concrete to scaling when exposed to natural weathering. This report describes the investigations made to answer these additional questions and gives the results of these investigations as well as the results of those studies which were incomplete when the first report was published. It also summarizes three investigations of portland blast-furnace slag cements made by the Ohio River Division Laboratories, CE, and the Missouri River Division Laboratory, CE, in connection with actual construction projects (Appendixes A and B).

Revisions and Corrections to the First Report

3. Certain errors in the first report should be corrected as follows:

a. Page 1, paragraph 2: The following statement is made: "In the past few years a number of portland-cement companies have begun the manufacture of portland blast-furnace slag cement." This statement might be less ambiguous as follows: "In the past few years, the manufacture of portland

blast-furnace slag cement has been begun by a number of portland cement companies that had not previously made it." Portland blast-furnace slag cement has been made by the Green Bag Cement Division of the Pittsburgh Coke and Chemical Co. since 1938.

b. Page 1, paragraph 3, first sentence gives data on producers of type IS cement. Since there was one producer of type IS-A, this sentence should be revised to read: ...by six manufacturers at seven mills and experimentally by a seventh company.

c. Page 7, tabulation at top of page: In column 6, line 3, after "C_2S" insert an asterisk; in column 7, line 2, after "$\alpha' C_2S$" add ", melilite."

d. Page 11, tabulation in center of page: The values given in columns 3 and 5 under the heading "background" are actually values for net peak height obtained by subtracting background from total observed peak height. The values for background and net peak height are:

Serial No.	Portland-Cement Clinker Back-ground	Portland-Cement Clinker Net Peak Height	PB-FS Cement Back-ground	PB-FS Cement Net Peak Height
341	160	700	160	550
340	170	665	150	575
339	210	740	200	460
342	200	580	180	410
345	220	670	170	420
337	180	750	160	385
338	170	690	230	405
336	150	960	160	400

e. Page 25, tabulation, column 2, last line: For "0.008" read "0.080."

f. Page 27, paragraph 44, first sentence: Delete that part of line 1 following "that," all of line 2, and all of line 3 through "however."

g. Table 4, heading of column 1: For "Proportions" read "Determinations."

h. Table 14, title: Delete "Reduction."

4. In paragraph 7 on page 3 of the first report it is stated that the ratio F II seems more closely related to hydraulic activity than the others. Values for F II may be added to the tabulation at top of page 5 as follows:

Slag Serial No.	F II	Slag Serial No.	F II
336	1.85	340	1.70
337	1.72	341	1.72
338	1.91	342	1.88
339	1.60	345	1.57

PART II: EFFECTS OF EARLY TERMINATION OF MOIST-CURING

Purpose of Tests

5. The Corps of Engineers Standard Practice for Concrete[1*] which was in force at the time this investigation was undertaken (1955) provided that "the normal 14-day curing period prescribed for concrete containing type II portland cement as the sole cementing medium shall be increased to 21 days when a cement-replacement material is used but need not be increased when a blend of type II portland with either natural cement or slag cement is used." No provision relating to portland blast-furnace slag cement was included because it was presumably believed that the use of portland blast-furnace slag cement might be considered (a) comparable to the case where portland cement is used with granulated blast-furnace slag as a cement-replacement material, or (b) comparable to the use of either portland cement or a blend of portland cement and slag cement. The tests described in Part I of this report were undertaken to develop data on whether concrete made with the portland blast-furnace slag cements tested was or was not significantly more adversely affected by premature termination of moist-curing than was concrete made with the reference type II portland cement. Based in part on informal consideration of the results of the work covered in this report, the Corps of Engineers 1962 Standard Guide Specifications for Concrete[2] included a provision in paragraph 15a for 14 days minimum moist-curing for concrete made using either type II or type V portland cement or portland blast-furnace slag cement.

Scope of Tests

6. Concrete mixtures containing 3/4-in. aggregate were prepared of the same materials and to the same proportions as those used in the basic program, and used for molding 3- by 6-in. cylinders and 3-1/2- by

* Raised numerals refer to similarly numbered entries in the Literature Cited which follows the text of this report.

4-1/2- by 16-in. beams. These specimens were moist-cured in the molds to an age of 3 days. Thereafter, half of the specimens were stored immersed in limewater until they were tested. The other half of the specimens were stored at 50 ± 5 percent relative humidity until they were either tested at 7 days age or until they reached an age of 28 days; then those that were to be tested at ages greater than 28 days were stored in laboratory air until tested. Cylinders were tested for compressive strength at ages of 7, 28, and 90 days, and 1 yr, and for Young's modulus of elasticity in compression at 28 days and 1 yr. Beams were tested for flexural strength (modulus of rupture) at 7, 28, and 90 days, and 1 yr, and portions of the beams broken in flexure at the 90-day age were tested for abrasion resistance. The test methods used were those used in the basic program.[3]

Materials, Mixtures, and Test Specimens

Materials used

7. The reference type II portland used in these tests (RC-376) was similar to that used in the basic program (RC-330), as the comparison of data in table 1 indicates. The aggregates also were similar to those used in the basic investigation. Since results of tests on the aggregate were not given in the first report, they are presented in table 2 of this report.

Proportioning of concrete mixtures

8. The nine concrete mixtures used were proportioned to have a cement content of approximately 5.5 bags per cu yd, a slump of approximately 2-1/2 in., an air content of approximately 6.0 percent, and a remolding effort of between 24 and 45 drops. The actual average properties were: slump, between 2-1/4 and 2-3/4 in.; air content, between 5.7 and 6.2 percent; and remolding effort, between 28 and 32 drops. As indicated in the following tabulation, the bleeding of the freshly mixed concrete in these supplementary tests was similar to that of the mixtures used in the basic investigation.

Cement Type and Serial No.	Bleeding, % Original Tests	Supplementary Tests
Portland type II:		
330, 376	3.0	2.2
Portland blast-furnace slag:		
337 (type IS)	4.1	4.1
338 (type IS)	3.1	2.2
339 (type IS)	3.5	4.4
340 (type IS)	5.2	4.9
341 (type IS)	3.8	3.6
345 (type IS)	4.1	3.2
342 (type IS-A)	2.1	3.0
336 (experimental, high MgO)	1.9	1.8

Concrete specimens

9. From each mixture, six rounds of test specimens were made, on six different days. In each round, eight cylinders for compressive strength tests and eight beams for flexural strength tests were made. One specimen of each type from each round for each type of curing was tested at each age.

Test Results

Compressive and flexural strength and modulus of elasticity

10. The results of the tests for compressive and flexural strength, and modulus of elasticity are given in table 3.

Abrasion resistance

11. To provide specimens for this test, the halves of the beams that had been broken in the flexural strength tests at 28 days and 1 yr age were again broken in half. The two end pieces were dried in air for 7 days, and two 2-in.-square areas on each of the two molded side faces were subjected to abrasion as described in paragraph 20 of the first report. Since six specimens for each type of curing were tested for each cement at each age, there were 96 sq in. of abrasion test area per test condition. Results expressed as loss in grams per square foot are given on following page, together with results for the 90-day specimens tested in the basic investigation for comparsion.

Cement Serial No.	Abrasion Loss, g/sq ft — Moist-Cured Until Tested: 28 days	90 days*	365 days	Moist-Cured 3 days: 28 days	365 days
330-376	128	104	100	129	68
337	153	124	116	288	194
338	165	101	156	273	184
339	177	117	142	288	214
340	189	122	130	234	158
341	174	117	133	266	153
345	174	131	126	212	158
342	192	133	138	237	158
336	150	115	120	240	164

* From table 7 of first report.

Discussion of Results

12. The test results reveal that, almost without exception, the specimens that received no moist-curing after 3 days age showed lower compressive and flexural strength, lower modulus of elasticity, and higher abrasion losses than comparable specimens that received additional moist-curing after 3 days age.

Compressive strength

13. The compressive strength relations are shown graphically in two ways. Fig. 1 shows strength gain curves from ages of 7 to 365 days for

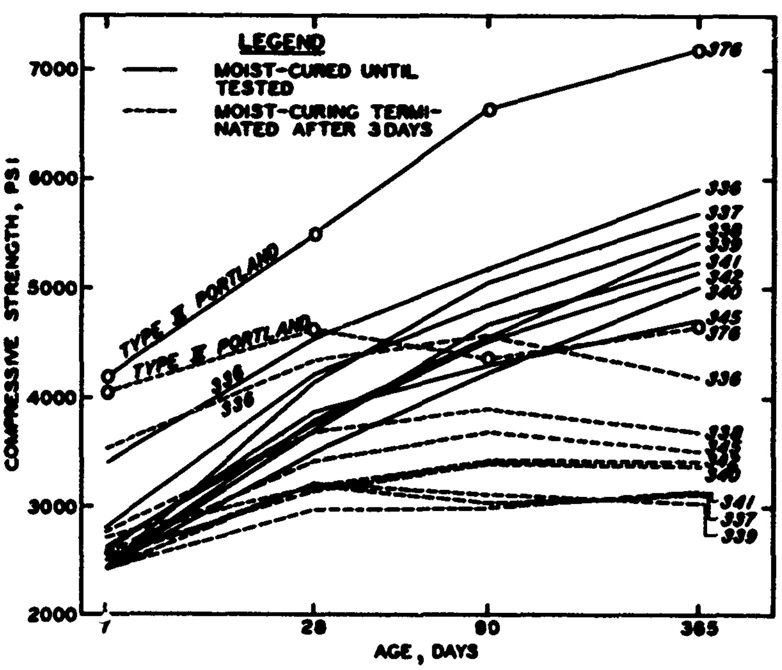

Fig. 1. Increase in compressive strength of concrete moist-cured continuously until tested and moist-cured for 3 days only

each concrete in each test condition. A tendency for the relative reduction in strength due to early termination of moist-curing to increase with increasing age is indicated. Fig. 2 compares the ratio of strength

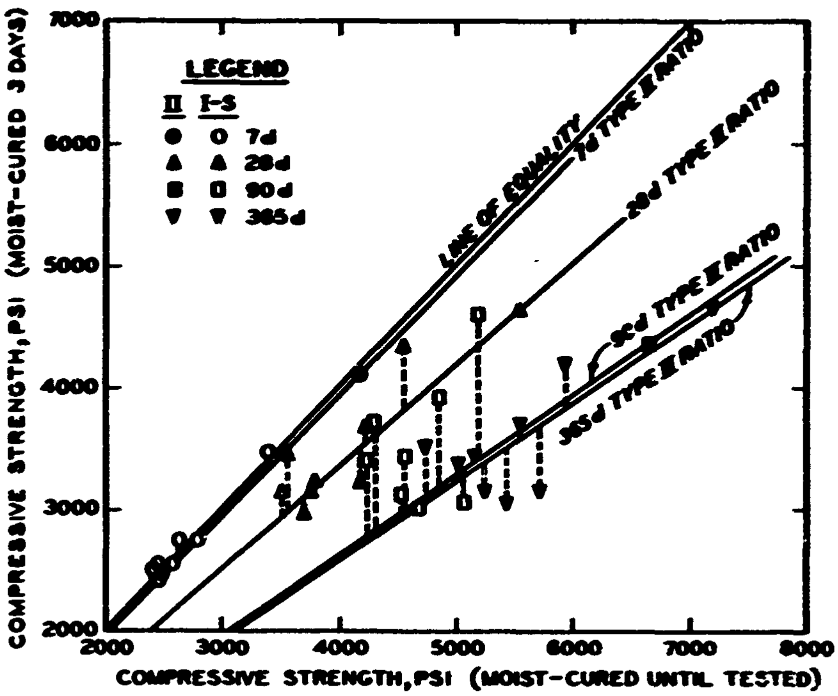

Fig. 2. Relative compressive strength of concrete moist-cured continuously and moist-cured for 3 days only

of continuously moist-cured specimens to that of comparable specimens whose curing was terminated at 3 days for each age. Lines are drawn for the ratios for the reference type II cement concrete at each age. A tendency for these lines to depart farther from the line of equality with increasing age is indicated. It is also indicated that, in general, the compressive strength of the portland blast-furnace slag cement concretes was not more severely affected by early termination of moist-curing than was that of the reference portland cement concrete.

Flexural strength

14. The flexural strength relations are shown in figs. 3 and 4, which are similar in construction to figs. 1 and 2. Fig. 3 indicates a general tendency, the reverse of that shown by fig. 1 for compressive

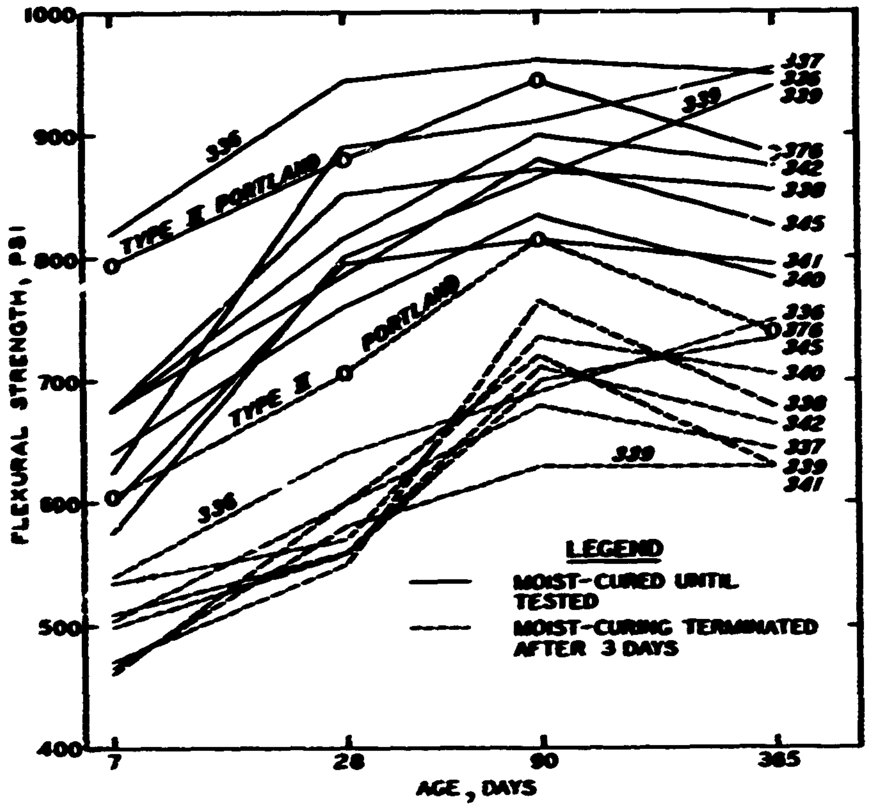

Fig. 3. Increase in flexural strength of concrete moist-cured continuously and moist-cured for 3 days only

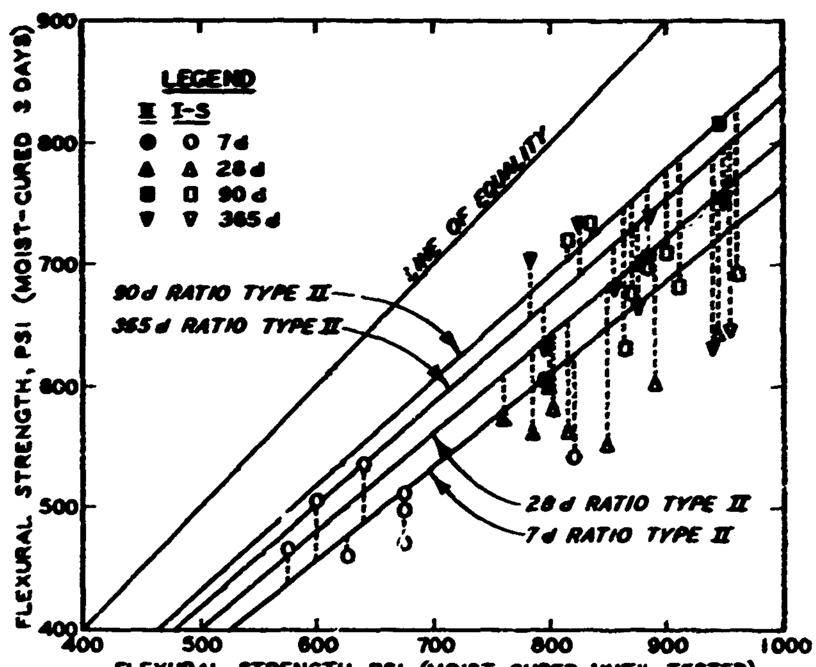

Fig. 4. Relative flexural strength of concrete moist-cured continuously and moist-cured for 3 days only

strength, for the reduction of flexural strength due to early termination of moist-curing to decrease with increasing age. Fig. 4 also shows a reverse tendency to that shown by fig. 2 for compressive strength, i.e., the lines for the ratios for the reference type II cement concrete tend to depart less far from the line of equality for flexural strength with increasing age. In general, it is also indicated that the flexural strength of the portland blast-furnace slag cement concretes may be slightly more severely affected by early termination of moist-curing than was that of the reference portland cement concrete.

Modulus of elasticity

15. At 28 days age all the concretes that had been moist-cured continuously had significantly higher moduli than those whose moist-curing had been terminated at 3 days. Between 28 and 365 days age, all the concretes that had continuous moist-curing showed increases in modulus of elasticity; those which had not received continuous moist-curing showed, in general, no increase in modulus and in a number of cases showed a decrease. The general relation is similar to that for compressive strengths (fig. 1); however, the separation of the two groups is more sharply defined at both ages (fig. 5).

Abrasion resistance

16. The abrasion resistance results are shown in fig. 6. It will be noted from these results that the early termination of moist-curing did not adversely affect the abrasion resistance of the reference type II portland cement concrete, but did adversely affect that of all the concretes made with portland blast-furnace slag cement. In these supplementary tests, the abrasion loss of the reference type II portland cement concrete was lower than that of any portland blast-furnace slag cement concrete at both ages and for both curing conditions. None of the portland blast-furnace slag cements made concrete that was consistently either more or less abrasion-resistant than did the others when the results of tests of specimens representing the two ages and curing conditions were compared.

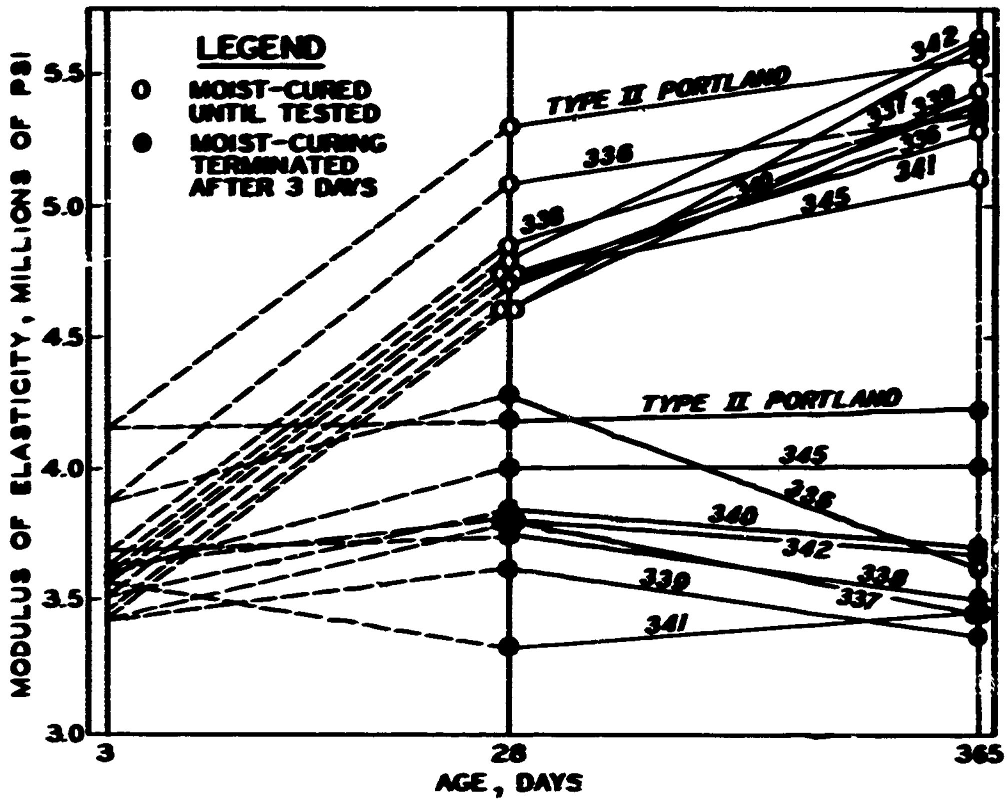

Fig. 5. Changes in modulus of elasticity between 28 and 365 days age of concrete moist-cured continuously and moist-cured for 3 days only

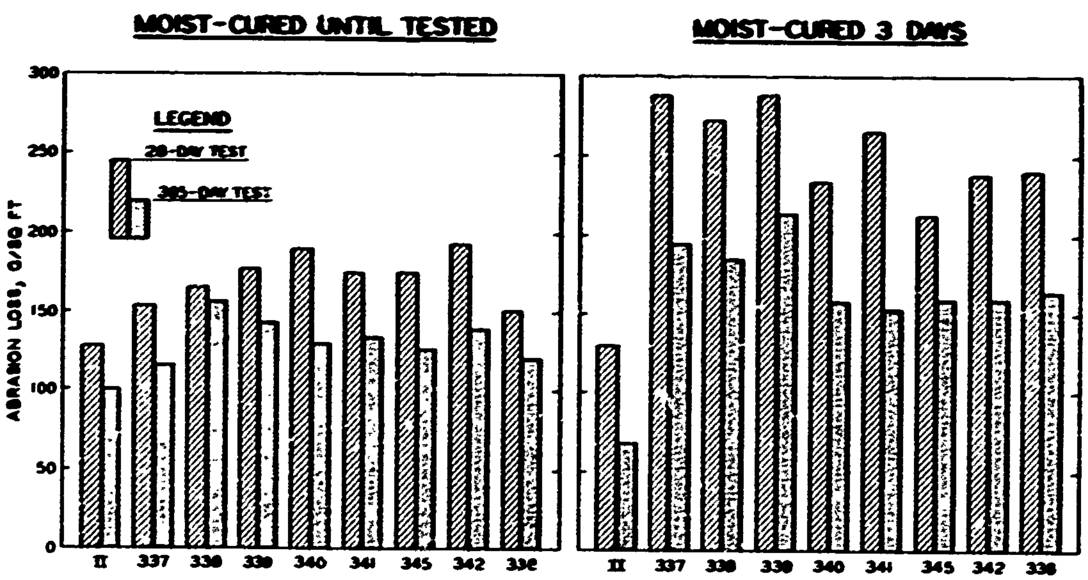

Fig. 6. Abrasion loss at 28 and 365 days of concrete moist-cured continuously and moist-cured for 3 days only

PART III: BOND TO AND CORROSION OF STEEL

Background

17. A number of publications in the literature, one of which was cited in paragraph 27 of the first report, refer to the possible harmful effects of constituents derived from the blast-furnace slag constituent of portland blast-furnace slag cements, usually the sulfide sulfur, on steel. The following references were provided subsequent to the preparation of the first report through the courtesy of Mr. W. J. McCoy of the Lehigh Portland Cement Co.

a. F. L. Brady:[4] "Concretes in which breeze and furnace clinker aggregates are used, cause rusting of steel reinforcement; the degree increases with increasing S content even though the aggregates are not acid. The substitution of sand for the finer part of coal residue aggregates reduces rusting as a result of reduction of accessible S compounds. The only clinker which when used in 1:6 concrete did not cause the rusting of steel in six weeks under moist conditions was a well-fused clinker, low in S, of unusually high quality from which all fines were removed and replaced by sand. When the fine aggregate was not removed corrosion occurred. It is thought that the investigation proves the undesirability of using coal residues as aggregates in concrete reinforced or in contact with steel."

b. A. F. Otten:[5] "Fe in concrete contg. boiler slag is subject to electrochem. corrosion. Elements constructed of Fe, H_2O and cement contg. slag had E approx. 0.3 v. and i p.2-0.15 ma. Reinforced concrete that is to be subjected to moisture should not be made from boiler slags."

c. Chemical Week:[6] "Japan's Construction Ministry last week predicted that a new cement process, developed by the ministry's Dr. Toru Mori, will produce cement 'superior to Portland cement in many ways - and from $1.45 to $2.75 cheaper than Portland.' The process could benefit Japan's iron and steel producers by utilizing the slag they now dispose of at a high trucking cost.

"Called No. 2 blast-furnace cement, the product is made by mixing limestone and blast-furnace slag. Mori succeeded in doing this (where others before him had failed) by devising a method of pulverizing the materials separately, later blending them in 50-50 and 40-60 proportions.

"The finished cement is said to be highly water-resistant, able to withstand temperatures up to 400 C. Because it is more corrosive than ordinary cements, it's not suited to steel-concrete building construction."

d. Jour. of Commerce:[7] "A new cement described here as 'superior to the conventional Portland cement in many ways,' has been developed by a government scientist.

"Named 'No. 2 Blast Furnace Cement,' this item is said to be extraordinarily cheap, water resistant once it forms, and able to withstand temperatures up to some 400 degrees Centigrade.

"It takes approximately half an hour longer to harden than ordinary cement, which makes it easier to handle in general construction work.

"Uses Limestone and Slag

"The cement is a mixture of limestone and blast furnace slag, obtained from iron and steel processing. Many similar kinds of cement have been produced since the end of the Pacific War but had to be discarded because of poor performance and quality.

"The inventor is Dr. Toru Mori of the Ministry of Construction Research Institute. He succeeded in manufacturing the cement after two years of research to modify the past methods of mixing the two raw materials. He eventually came up with a method of pulverizing the limestone and slag separately and then mixing them in proportions of 50 to 50, and also 40 to 60 percent.

"The cost of making this new cement, according to the Construction Ministry, is between $1.45 and $2.75 lower than an average of $17.50 per ton required for producing Portland Cement. Moreover, the iron and steel industries are expected to benefit from this new-type cement's production because it will use slag which they have so far had to dispose of at a high trucking cost.

"A Construction Ministry official told The Journal of Commerce that an estimated $8 million will be saved by utilization of the slag produced by the iron-steel manufacturers at the rate of 500 kilograms to a ton of pig iron.

"Production Under Way

"Various iron and steel and cement manufacturers are reported to have already commenced or are soon to start production of this new-type cement. Construction companies, especially in the Osaka-Koge area, are also looking forward to the new product.

"Building experts agree that the new material is

strongly resistant to heat and water, making it ideal for fireproof mortared block houses, river and harbor embankments, and dams. But it is not suited, Ministry officials say, for tall buildings of a ferroconcrete structure, because it corrodes iron faster than ordinary cement.

"Some of the new cement will in all probability be exported to the Chinese Communist mainland, for construction of a dam there, it is also reported."

Purpose of Tests

18. No specifications for concrete construction in the United States are known which prohibit the use of portland blast-furnace slag cement in reinforced or prestressed concrete; however, the specifications for the product limit the sulfide sulfur content to a maximum of 2.0 percent. The tests described in the following paragraphs were undertaken to develop data on whether or not concrete made with portland blast-furnace slag cements of high sulfide sulfur content would manifest significantly reduced bond to steel or significantly greater corrosion of embedded steel than concrete made with the reference type II portland cement.

Scope of Tests

19. The two portland blast-furnace slag cements of highest sulfide sulfur content of those used in this investigation were selected for these tests. They were:

	Sulfide Sulfur Content, %	
Cement	Slag Constituent	Portland Blast-Furnace Slag Cement
338	1.68	0.73
339	1.51	0.67

The reference portland cement (376), the aggregates, and the concrete mixtures were the same as those used in the investigation of the effects of early termination of moist-curing. Four specimens were made with each of the three cements in each of six rounds; each specimen was a 6-in. cube and contained one No. 6 steel bar embedded vertically. These specimens were tested for strength of bond to steel in accordance with method CRD-C 24-57,[3] half at an age of 28 days, and the remainder at an age of 90 days. Additional specimens, 8-3/4 by 8-3/4 by 12 in., were made, each containing four pieces of completely embedded steel for

corrosion-resistance tests. Two of the pieces of steel were 10 in. long and so located as to have a minimum of 1 in. of cover, and two were 6 in. long with approximately 3 in. of cover. A total of 45 of these specimens were made with each cement; 30 were moist-cured at the laboratory, and the remaining 15 were removed from moist-curing after 14 days and later installed on the Waterways Experiment Station (WES) sea-water exposure rack at St. Augustine, Florida. Half of the 30 laboratory-stored specimens of each cement were broken open for inspection at an age of 90 days, the remainder at 1 yr. The specimens exposed at St. Augustine were brought back to the laboratory to be broken and inspected in groups of 6, 6, and 3 of each cement after 2, 4, and 5 years of exposure, respectively.

Test Results

Bond to steel

20. The nominal average bond stresses for the 12 specimens tested for each concrete at each age were calculated at five increments of slip at the loaded end of the bar. The results, also shown graphically in fig. 7, were as follows:

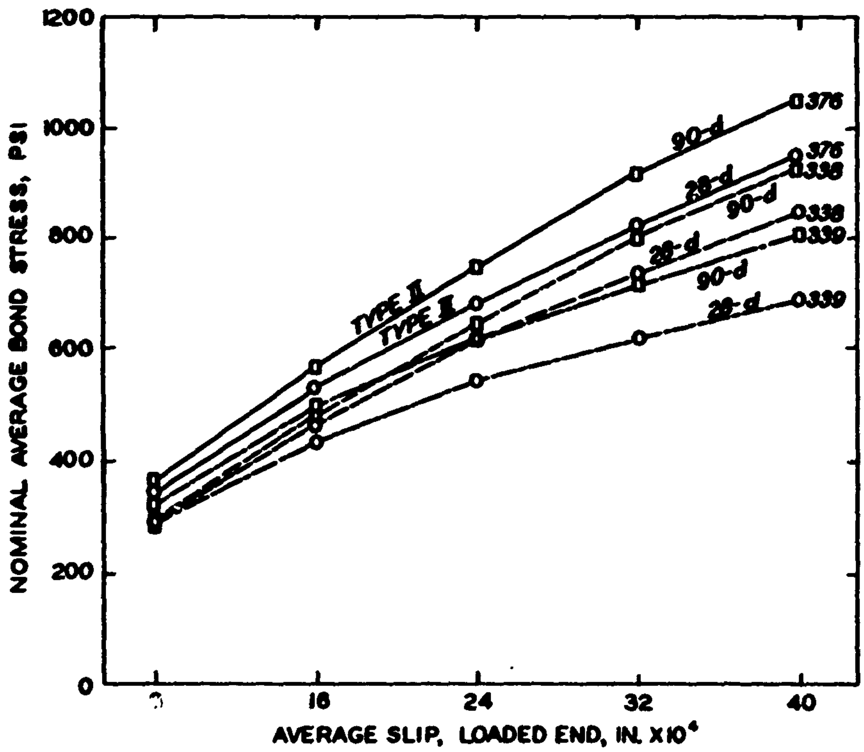

Fig. 7. Stress-slip curves for concrete tested at 28 and 90 days age

Slip, in. x 10^4	Nominal Average Bond Stress, psi					
	28 days			90 days		
	376	338	339	376	338	339
8	340	290	290	360	290	320
16	530	460	430	570	480	490
24	680	610	540	750	640	620
32	810	730	610	910	800	710
40	940	840	680	1040	920	800

21. The relation between bond stress at a slip of 0.004 in. and compressive strength of specimens of comparable concrete at 28 and 90 days is shown in fig. 8. The bond strength-compressive strength relation indicates a slightly higher relative bond strength for concrete made with cement 339 or the reference type II portland cement. The increase of bond strength with age parallels the increase of compressive strength.

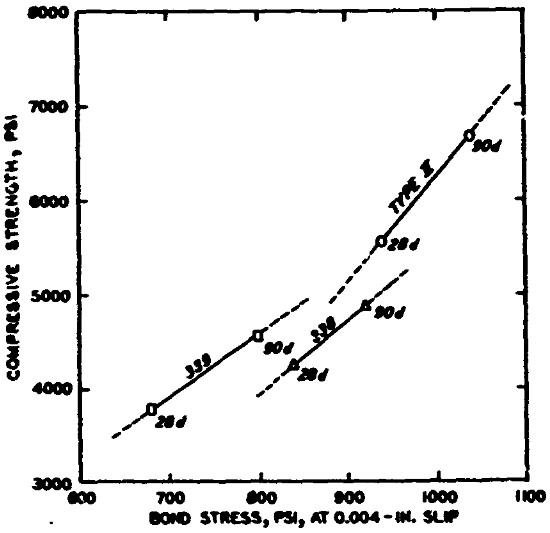

Fig. 8. Relation of bond stress to compressive strength of concrete

Corrosion of steel

22. The corrosion-resistance test specimens were broken in compression so that the four pieces of embedded steel could be removed and examined. Rust was found mainly on the lower surfaces of the bars where bleeding water had accumulated in an underside void. It was also observed that the 10-in. bars originally positioned to be 1 in. below the top surface and 1 in. in from one side, with 1 in. of cover at each end, had settled during consolidation so that the average depth from the top surface of the specimen to the bar was 2.4 in. The 6-in. bars originally positioned to be 3 in. above the bottom and 3 in. from one side, with 3 in. of cover at each end, had also settled so that they were, on the average, 1.6 in. above the bottom. Rusting and corrosion of the surfaces of the steel bars were classified by size and number of spots (table 4). In size the rusted areas were classified as

"pinpoints" (nominal 1/32-in. circles), 1/16-, 1/8-, 1/4-, 1/2-, and 3/4-in. spots. The pinpoints were regarded as having unit area; the 1/16-in. spots an area of 4; the 1/8-in. spots, 16; and the 1/4-in. spots, 64, etc.

Petrographic examination

23. The 18 specimens brought back from St. Augustine at the 2-year age were examined petrographically as described in the following paragraphs.

24. Petrographic examination was made of the fragments which remained after the prisms had been split and the rust spots on the steel bars counted. The specimens contained 3/4-in. maximum size limestone (VICK-3 G-1(12)) and natural sand (WES-1 S-8(3)). The concrete mixtures had been proportioned to have cement contents of 5.5 bags per cubic yard, air content of 6.0 $\pm$ 0.5 percent, and slump of 2-1/2 $\pm$ 1/2 in.

25. The pieces of reinforcing steel and the fragments of concrete were examined visually and with a stereomicroscope. Thin sections were made from concrete representing each cement, and these thin sections were examined with a petrographic microscope.

26. The evidence for alkali reaction with the chert in the fine aggregate (natural sand) was clearest in the sections containing plain portland cement, and appeared as cloudiness of paste near chert, peripheral cracking around chert, and "tensile" cracking in chert. The paste of the portland blast-furnace slag cements was typically dark, cloudy at high magnification, and low in $Ca(OH)_2$ at two years, with abundant unhydrated slag and little cement clinker to be found. There was, however, some very suspicious-looking cracking in chert in sections made from both portland blast-furnace slag cements. The mortar-coarse aggregate bond in all specimens was good. An attempt was made to correlate the areas of rust on the bars with areas where the bond between steel and concrete was poor or lacking; it appeared, however, that the location of the rust spots was independent of the nature of the bond. The results of the examination are tabulated on the following page.

Condition of Steel	Condition of Concrete	Color of Paste
	Cement 376 (Type II)	
Slight to moderate rusting. More rust on the long pieces of steel than on the short pieces.	Virtually unaffected. Negligible sulfoaluminate. Negligible alkali-aggregate reaction. The paste nearer the outer surfaces was carbonated and/or leached with secondary enrichment of calcium hydroxide. There were tiny aragonite crystals either filling or partially filling voids near outer surfaces.	Light gray (N 7). Scattered thin areas of paste (1/16 to 1/8 in.) at or near the outer surfaces were cream colored.
	Cements 338 and 339 (Type IS)	
Virtually no rusting. More rust on long pieces of steel than on short pieces.	As reported for 376, with abundant unhydrated slag, typical dark slag cement paste.	White (N 9). Some of the bluish areas did not fade completely after exposure to air; they were light bluish-gray (5 B 7/1). Scattered thin areas (1/16 to 1/8 in.) at or near the outer surfaces were cream colored.

Discussion of Results

27. It will be noted (from table 4) that the total amount of corrosion in both exposures at all ages was greatest for the concrete made with the reference type II cement, less for the concrete made with the portland blast-furnace slag cement of lower sulfide sulfur content, and least with the portland blast-furnace slag cement of higher sulfide sulfur content. The amount of corrosion exhibited by the bars in the reference concrete increased between 90 and 365 days, but there was no increase in corrosion for the bars of portland blast-furnace slag cement concrete. It is concluded that, under the conditions of these tests, the presence of sulfide sulfur in the portland blast-furnace slag cements did not cause corrosion of embedded reinforcing steel.

28. Two articles in the literature support these results. Ost and

Monfore[8] compared performance of steel prestressing wire in concretes made with three type I portland cements and five portland blast-furnace slag cements and found that after one year, there was little if any relation between sulfide content of cement and corrosion, no more corrosion being found when portland blast-furnace slag cement was used than when type I portland cement was used. The portland blast-furnace slag cements used in the work reported by Ost and Monfore had sulfide sulfur contents ranging from 0.24 to 0.82 percent.

29. Lea and Watkins[9] summarized results through 1960 of a study begun in 1929, and found that (a) the primary cause of deterioration of reinforced concrete piles was corrosion of the reinforcement; (b) the cement content and thickness of cover were of major importance in determining durability; and (c) with a normal mixture and 2-in. cover, cracking occurred in concretes made with portland cements by 10 years but when portland blast-furnace slag cement, high-alumina cement, or portland-trass (pozzolan) cements were used, no cracking occurred.

PART IV: SULFATE RESISTANCE

Background

30. Paragraphs 37-42 of the first report describe the two kinds of performance tests for sulfate resistance that were used in the basic program and discuss the results obtained. One test,[10] using mortars to which additional calcium sulfate was added during mixing, gave a clear separation of the cements apparently as a function of the amount of tricalcium aluminate in the portland cement clinker component. The other test, involving storage of concrete cylinders in sulfate solution, had yielded no significant results. The possibility was suggested that the mortar test with added sulfate permitted sulfate reaction at such an early age that the activity of the silica in the slag had not become effective in improving sulfate resistance. Additional data have been developed from both of these types of tests and also from a third, the lean mortar bar test.[11] Additional data on the properties of the materials as related to sulfate resistance have also been developed. These additional data are discussed in the following paragraphs.

Tests of High-C_3A Portland Cement and Slag Blends

Sulfate resistance of two high-C_3A portland cements

31. Two portland cements of high calculated tricalcium aluminate content were selected for the investigation of the effect of granulated blast-furnace slag in reducing sulfate attack. Results of tests for properties of these cements are as follows:

Test	Cement 332	Cement 334
SiO_2, %	19.4	21.1
Al_2O_3, %	7.0 (6.98)	6.3 (6.27)
Fe_2O_3, %	2.5 (2.53)	1.9 (1.88)
CaO, %	63.7	63.6

(Continued)

Test	Cement 332	Cement 334
MgO, %	2.7	2.9
Na_2O, %	0.37	0.13
K_2O, %	0.95	0.16
Total as Na_2O, %	1.00	0.24
C_3S, %	55	48
C_2S, %	14	24
C_3A, %	14 (14.3)	13 (13.5)
C_4AF, %	8	6
S.A,a.p.cm^2/g	3290	3550
Comp. str, psi		
3 day	2510	1700
7 day	3735	2840
28 day	4660	4835

32. Cement 332 had 0.8 percent more C_3A than cement 334 when C_3A was calculated from chemical analysis. When the C_3A content was calculated using the procedure* given by Swayze,[12] their relative positions were reversed with cement 332 indicated to have 9.9 percent and cement 334 indicated to have 10.2 percent. X-ray diffraction studies of samples of these cements indicated that the peak at 2.70 angstrom units, characteristic of crystalline C_3A, had nearly twice the intensity for cement 332 (195 counts per sec) as for cement 334 (100 counts per sec). Cement 332 also had a high alkali content, 1.00% Na_2O equivalent, and cement 334 a low alkali content, 0.24% Na_2O equivalent.

33. These two cements were subjected to both the lean mortar bar test and the mortar bar test with added sulfate. The latter test was run on two occasions, nearly a year apart. A summary of the results is given in table 5.

34. The expansion shown by mortars containing cement 334 was

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* As given in Amer. Jour. Science, vol 244, 1946: If Al_2O_3/Fe_2O_3 ratio is 1.6 or higher and the clinker contains sufficient MgO or alkalies to lower the invariant temperature to 1300 C or below, the ferrite phase will be C_6A_2F and 1.276 x wt of Fe_2O_3 = wt of Al_2O_3 in C_6A_2F. Total Al_2O_3 - Al_2O_3 in C_6A_2F = residual Al_2O_3. Residual Al_2O_3 x 2.65 = C_3A.

greater than that shown by mortars made with cement 332 at ages up to 30 days and after 60 days, but cement 332 mortars showed a greater expansion in the intermediate period from about 30 to 60 days age. These relations are shown in fig. 9, and are summarized as follows:

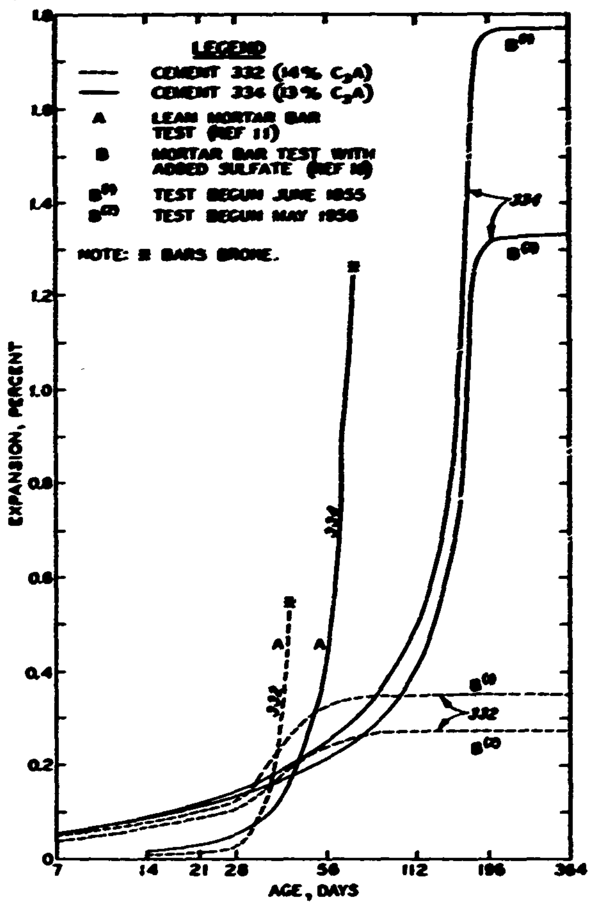

Fig. 9. Comparison of results of sulfate resistance tests on two high-C_3A portland cements

Test		Cements 332	Cements 334
C_3A, chemical analysis, %		14.3	13.5
C_3A, chemical analysis, % (Swayze)		9.9	10.2
C_3A, X-ray, cps, 2.70 Å		195	100
Na_2O equivalent, %		1.00	0.24
Expansion, %, at:	28 days, added sulfate test 1	124	142
	added sulfate test 2	105	130
	lean mortar bar test	27	51
	35 days, lean mortar bar test	117	93

(Continued)

Test		Cements 332	334
Expansion, %, at:	42 days, lean mortar bar test	532	160
	70 days, lean mortar bar test	--	1235
	84 days, added sulfate test 1	346	354
	added sulfate test 2	263	295
	196 days, added sulfate test 1	348	1762
	added sulfate test 2	269	1312
	364 days, added sulfate test 1	354	1772
	added sulfate test 2	272	1332

Effects of blending slags with the high-C_3A portland cements

35. Two granulated blast-furnace slags were used to replace 40 percent by absolute volume of each of the two cements; then the two types of mortar bar tests were made. Both of the slags were found by microscope examination to contain more than 90 percent glass. Slag 216(4) had a surface area (air permeability) of 4270 sq cm/g, and slag 296, 3495 sq cm/g.

36. Lean mortar bar test results. The results of the lean mortar bar tests are shown graphically in fig. 10, and are summarized as follows:

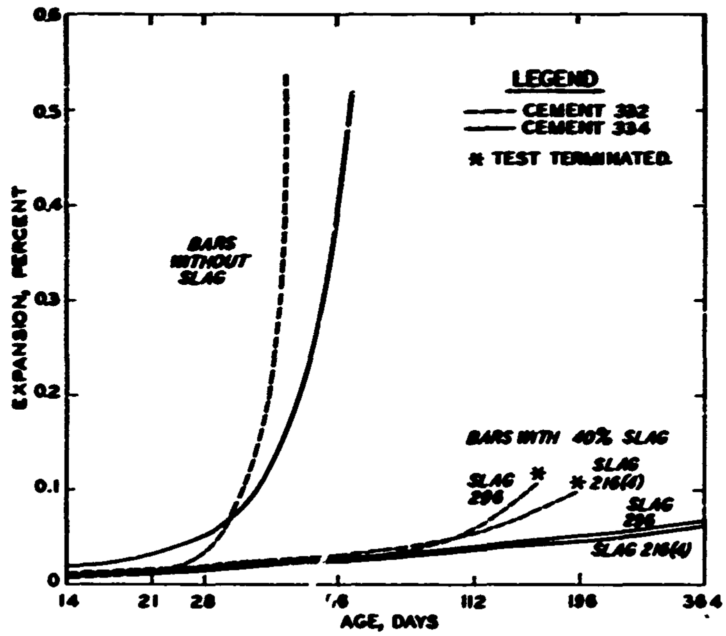

Fig. 10. Effects of two slags in reducing expansions of lean mortar bars made with two high-C_3A portland cements

Age, days	Average Expansion, percent x 10^3			
	Cement 332		Cement 334	
	Slag 296	Slag 216(4)	Slag 296	Slag 216(4)
70	36	42	31	36
154	109*(110, 129, 124, 73)**	79	44	48
196	--	104*(120, 125, 84, 87)**	48	52
364	--	--	70(81, 77, 71, 53)**	68(73, 71, 65, 63)**

* Test terminated when average expansion exceeded 0.100 percent.
** Values in parentheses are expansions measured on the four bars at end of test.

37. These results suggest that the slags were effective in greatly reducing the expansion due to sulfate attack. They also suggest that:

a. Both slags were less effective in reducing expansion in mortars made with cement 332 than those made with 334.

b. Slag 296 was less effective in reducing expansion in mortars made with both cements than was slag 216(4).

38. Added-sulfate mortar bar test results. The slags were also used to replace 40 percent of the two cements in mortars with added sulfate. The results of these tests are summarized in the following tabulation; the relations between the results are shown graphically in fig. 11.

Age, days	Expansion, percent x 10^3			
	Cement 332		Cement 334	
	Slag 296	Slag 216(4)	Slag 296	Slag 216(4)
7	48	49	57	55
14	75	83	79	86
21	95	111	99	108
28	117	133	115	126
56	205	153	169	191
84	222	155	228	228
112	221	155	303	238
140	222	156	329	242
252	223	156	331	248
364	224(238, 234, 229, 215, 212, 216)*	157(159, 156, 157, 156)	333(326, 324, 341, 355, 338)	240(261, 260, 264, 238, 240, 239)

* Values in parentheses are expansions measured on the four bars at end of test.

39. In these tests the slag again reduced the expansion, but by a much less marked amount than in the lean mortar bar tests and, again, slag 296 was less effective with both cements than was slag 216(4). However, in these tests the expansion of bars containing slags and cement 332 was less than that of bars containing slags and cement 334. It is difficult to decide whether the slags were less effective with cement 334 (the reverse of the comparable conclusion from the lean mortar date), or whether the difference is in the relative degree or rate of reaction of the two cements to the two sets of test conditions. Relative reaction rates may be estimated by the strength gains shown in fig. 12. It will be recalled that no conclusion was reached from the performance of the cements without slag as to which cement had lower sulfate resistance.

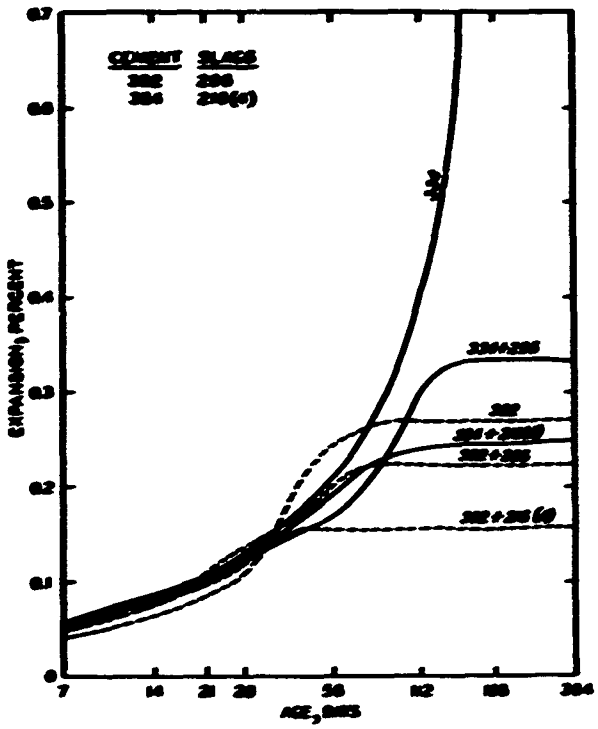

Fig. 11. Effects of two slags in reducing expansions of added sulfate mortar bars made with two high-C_3A portland cement

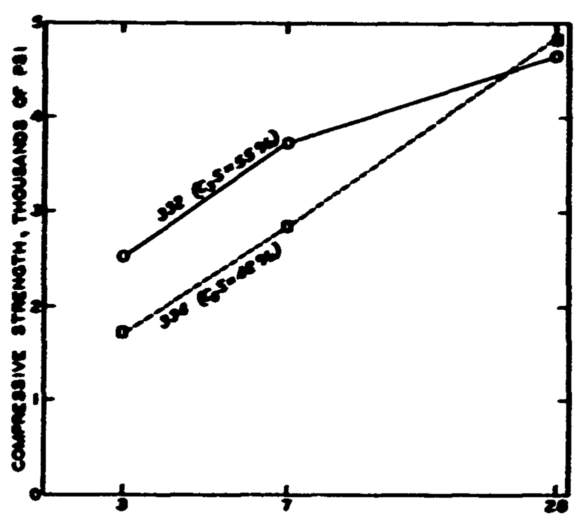

Fig. 12. Relative strength gain rates of two high-C_3A portland cement

40. Discussion of results. It is believed that there are important differences both between the two cements and between the two testing procedures employed. These differences appear to be related to the following:

a. Cement 332 showed a rapid expansion between 30 and 60 days age in both tests, which was suppressed by slag in the lean mortar bar tests, and

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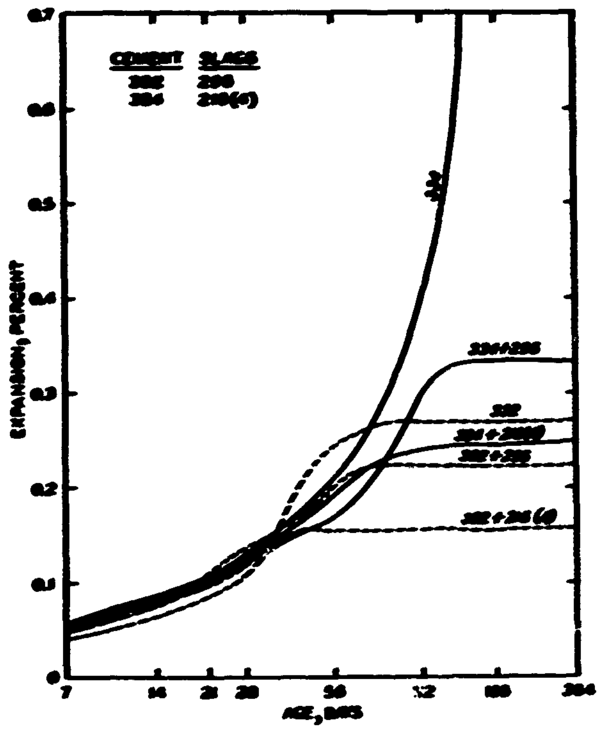

Fig. 11. Effects of two slags in reducing expansions of added sulfate mortar bars made with two high-C_3A portland cement

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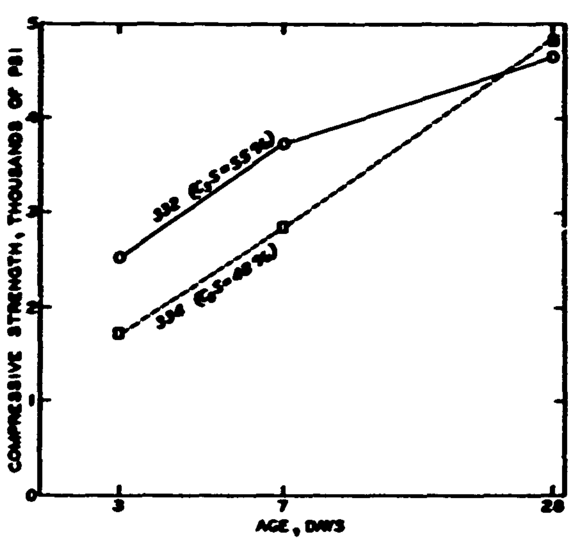


Fig. 12. Relative strength gain rates of two high-C_3A portland cement

partially suppressed by slag in the added-sulfate mortar bar tests. Cement 334 showed no such intermediate period of rapid expansion.

b. Cement 334 showed steady progressive expansion until, in the case of the added-sulfate mortar bar tests, a maximum was reached and a relatively constant length maintained.

c. The lean mortar bar test results were characterized by continuous expansion until either the bars broke or the test was terminated.

d. The added-sulfate mortar bar test results were characterized by increasing expansion until a maximum was attained, after which a relatively constant length was maintained.

41. It is believed that the "leveling off" indicated in the results of the added-sulfate mortar bar tests was produced by the effective termination of the production of the expansive reaction product due to the chemical reaction having come to an end through the effective exhaustion of the available supply of one reactant. The reaction product was either high-sulfate calcium sulfoaluminate ($3\ CaO.Al_2O_3.3\ CaSO_4.31\ H_2O$) or low-sulfate calcium sulfoaluminate ($3\ CaO.Al_2O_3.CaSO_4.12\ H_2O$), presumably, in normal circumstances, wholly or predominately the former. Since the SO_3 content of the mortars was brought to a constant value of 7 percent by weight of the cement, it follows that there was enough SO_3 in the mortar to combine with 7.87 percent C_3A by weight of cement to form high-sulfate calcium sulfoaluminate or to combine with 23.62 percent C_3A by weight of cement to form low-sulfate calcium sulfoaluminate.

42. From fig. 9 (page 22) it appears that cement 334 mortar yielded materially more expansive reaction product than cement 332. This cannot be interpreted to mean that cement 334 contained materially more C_3A than did cement 332, since (a) chemical data indicated essentially identical C_3A contents, (b) X-ray diffraction data suggested that 332 had more C_3A than 334, and (c) the SO_3 content was such that the production of reaction product would cease before all the C_3A in either cement was reacted to form high-sulfate calcium sulfoaluminate. It is therefore suggested that while the "leveling off" does indicate the effective exhaustion of the supply of one reactant (the sulfate ion) the amount of expansion indicated at the point of leveling off may be a function of the relative age (strength) of the mortar at the time the major expansion occurred as well

as a function of the amount of reactants available. Referring again to fig. 9, it is suggested that these relations may actually indicate that cement 332 is materially less sulfate-resistant (and contains materially more sulfate-reactive C_3A) than cement 334, in spite of the uniform indication of higher ultimate expansion by bars made with cement 334. This suggestion is based on the following considerations: The rapid reaction and expansion of all bars made with cement 332 between the ages of 30 and 60 days may have so weakened the physical structure and mechanical continuity of these bars as to make them incapable of large additional linear axial elongation; thus further reaction and formation of further expansive reaction product resulted in lateral swelling without significant increase in length. Bars made with cement 334, that did not undergo such a rapid reaction and expansion between 30 and 60 days age, showed greater ultimate expansion, even though a lower amount of reaction product was formed, because they had not been weakened between the ages of 30 and 60 days and hence could continue to exhibit such linear expansion as the reaction product could produce.

43. The lean mortar bar testing procedure, which indicates an ultimate expansion for all bars with slag of only 20 percent or less of that of bars without slag, is regarded as giving more "realistic" indications of the quantitative magnitude of the reduction in expansion to be expected from the use of slags such as these with high-C_3A cements. This opinion is based on the fact that in this procedure, as in natural sulfate exposures, the cement (or cement and slag) has an opportunity to hydrate to a considerable degree before the sulfate becomes available in the interior of the paste to react and produce sulfoaluminate. The test using added sulfate appears to give excellent quantitative indications with portland cements alone, perhaps because the effects of the reaction with sulfate are not materially modified by initiation of the reaction at a very early age.

44. A summary of selected test results is given in table 6. From the foregoing discussion and the selected data in table 6, the following conclusions appear indicated:

- a. Cement 334 showed higher ultimate expansion than cement 332 in both tests.
- b. Both slags reduced the expansion of both cements.
- c. Cement 332 is probably the less resistant to sulfate attack in spite of its lower ultimate expansion, since both slags

in both tests were less effective, either absolutely or proportionately, in reducing its expansion.

d. The lean mortar bar test is regarded as giving a more realistic indication of the amount by which a slag will reduce sulfate expansion.

Tests of Portland Blast-Furnace Slag Cements

45. The data on blends of two slags with each of two portland cements of high tricalcium aluminate content tested by both the lean mortar bar method and the added sulfate mortar bar method, given in the preceding section, are regarded as providing a basis for discussion of the results of these tests on portland blast-furnace slag cements as given below.

Scope of tests

46. The nine portland cements and three blends of portland and natural cements studied in the basic investigation have been subjected to test for sulfate resistance in three ways: (1) tests of mortar bars with added sulfate; (2) sulfate exposure of lean mortar bars; (3) sulfate exposure of concrete cylinders. Table 12 of the first report gives results of the mortar bar tests with added sulfate to an age of 140 days (these data were also plotted in fig. 10, and discussed in paragraphs 37 through 41 of that report). The lean mortar bar tests were initiated subsequent to the preparation of the first report. The sulfate exposure of concrete cylinders is mentioned in paragraph 40 of the first report.

Results of mortar bar tests

47. Mortar bars with added sulfate. The expansion of these specimens to an age of 1 yr is given in table 7 and plotted in fig. 13. The results of the original tests show, as indicated in table 7, good concordance of results for individual specimens for all cements except 341. A retest of cement 341 gave the results shown in table 7. It is concluded that one round of the original tests was probably made with some other cement inadvertently substituted for cement 341. Results of petrographic examination of the bars after they were 1 yr old are given in table 8.

48. Lean mortar bars. The nine cement and three cement blends were also tested by the lean mortar bar method.[11] The amounts of water used per batch, the flow values obtained, and the weights of the bars

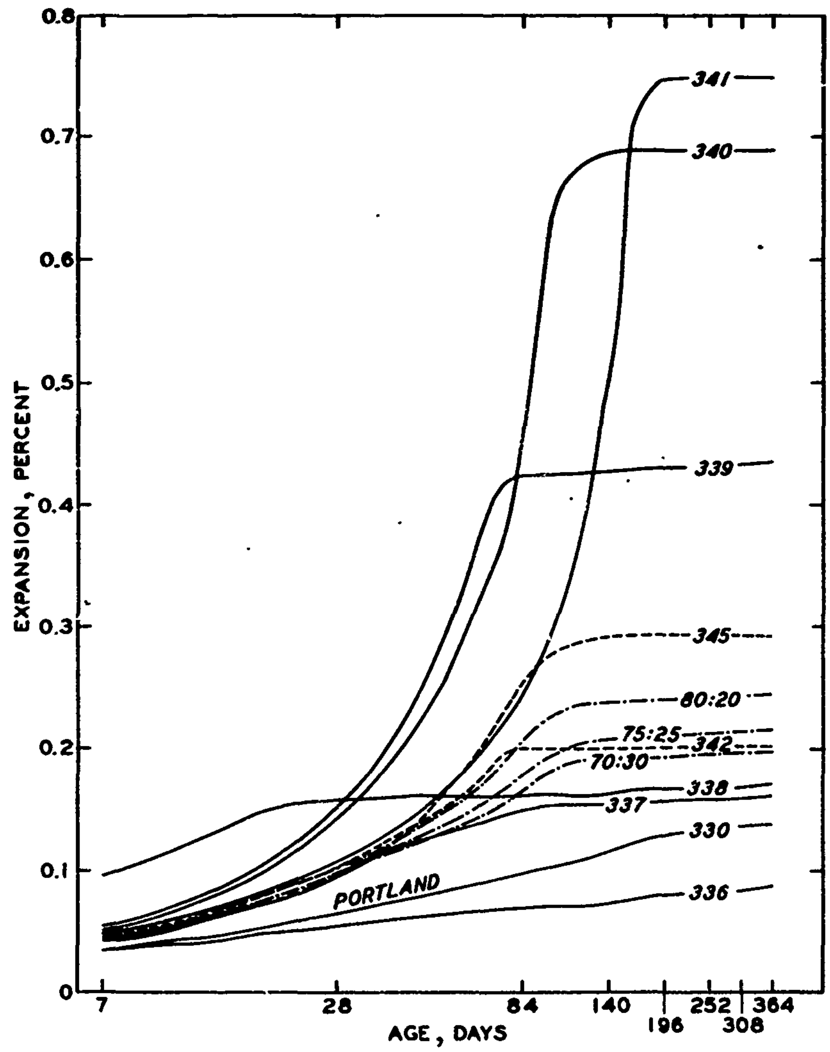


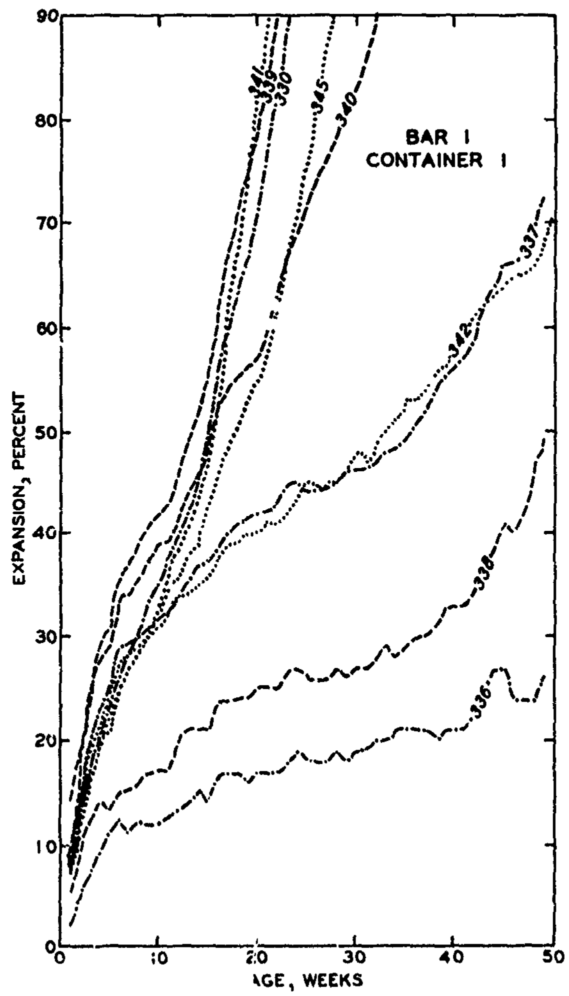
Fig. 13. Expansion of added-sulfate mortar bars made with portland cement, or portland blast-furnace slag cement, or portland blast-furnace slag cement and natural cement

were as follows:

Cement	Water ml	Flow %	Weight, g Bar 1	Bar 2	Bar 3	Bar 4
330	218	108	387.8	389.2	395.1	396.1
336	207	109	390.6	395.3	397.7	394.4
337	214	110	395.0	394.6	396.0	398.6
338	210	110	393.3	392.2	400.0	401.8

(Continued)

Fig. 14. Expansion of lean mortar bars in stronger sulfate solution



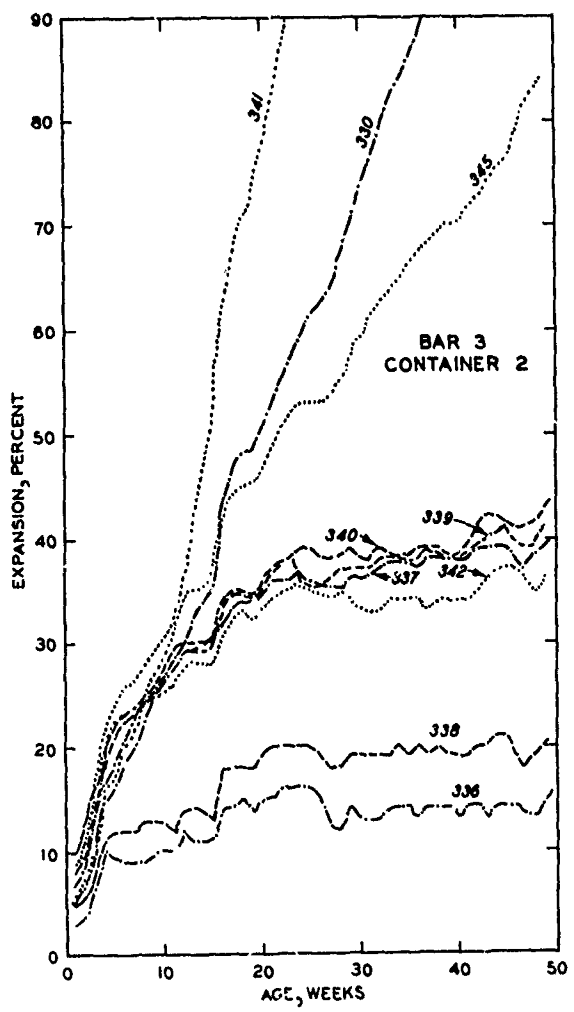


Fig. 15. Expansion of lean mortar bars in weaker sulfate solution

Cement	Water ml	Flow %	Weight, g Bar 1	Bar 2	Bar 3	Bar 4
339	221	110	392.8	396.7	397.7	395.0
340	218	104	388.9	385.6	396.7	393.2
341	216	107	394.8	399.1	396.2	396.2
342	216	108	381.1	378.4	383.0	385.7
345	210	111	386.0	387.4	389.7	395.2
80-20	216	109	386.1	378.0	389.9	396.2
75-25	214	111	379.5	378.4	394.6	392.5
70-30	212	104	385.5	381.9	390.3	390.0

49. Two bars were made per batch; two batches, made on different days, represented each condition. The 24 bars from round 1 were stored in one metal container, and those from round 2 in a similar container. Both containers were filled with a 5.0% (0.352M) solution of cp anhydrous Na_2SO_4. The solution level was maintained by adding water. The bars were measured each week. The expansion data for the two bars of each cement and blend in one container so deviated from the data for the two companion bars in the other container that in approximately 1 yr these differences had in some cases become very large. The solutions then in the two containers were tested and found to be as follows:

Solution	SO_3 ppm	SO_3 moles/liter	Na_2O ppm	Na_2O moles/liter*
Container 1	20,750	0.260	20,200	0.326
Container 2	506	0.0064	850	0.0137

* Required moles/liter of Na_2O was 0.352

50. The expansion of the bars in the two containers are indicated by the following tabulation and illustrated in figs. 14 and 15.

Expansion of Bars, thousandths of %

Cement	91 days Bar 1	Bar 2	Bar 3	Bar 4	182 days Bar 1	Bar 2	Bar 3	Bar 4	364 days Bar 1	Bar 2	Bar 3	Bar 4
330	40	38	30	29	111	106	61	60	315	311	129	122
336	13	13	12	12	18	18	16	17	25	24	14	16
337	34	34	28	26	44	43	36	34	75	70	39	37
338	20	21	14	16	26	28	20	22	54	59	20	25

(Continued)

Cement	91 days Bar 1	Bar 2	Bar 3	Bar 4	182 days Bar 1	Bar 2	Bar 3	Bar 4	364 days Bar 1	Bar 2	Bar 3	Bar 4
339	46	46	30	30	116	120	39	36	371*	402*	42	40
340	42	40	30	26	72	69	36	35	171	160	44	43
341	41	32	36	37	142	120	96	104	450*	391**	212	224
342	34	36	28	28	44	48	35	34	72	78	37	38
345	35	35	35	33	70	73	53	52	289	294	89	87
80-20	29	28	27	27	39	43	37	37	137	180	43	43
75-25	30	29	26	27	43	43	37	38	160	174	43	44
70-30	†	28	25	27	--	42	38	38	--	135	45	46

Expansion of Bars, thousandths of %

* Reading at 294 days, after which bars broke.
** Reading at 280 days, after which bars broke.
† Broke at 56 days (expansion 0.024%).

Fig. 16 compares the expansions for two cements in the two environments.

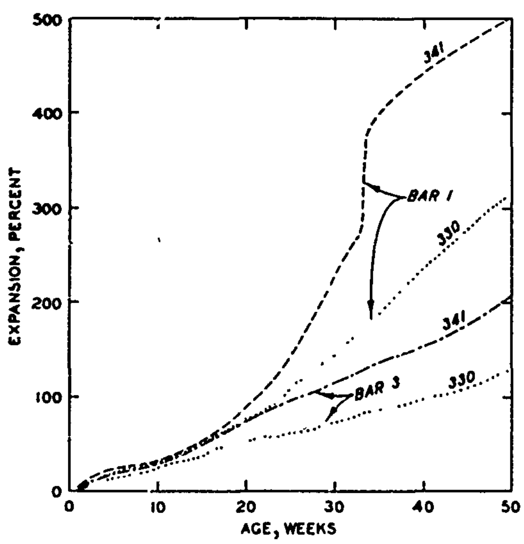


Fig. 16. Comparison of expansions of bars made with two cements stored in solutions of differing concentration

51. The sulfate concentration of the solution in container 2 was increased to that specified for the test, and the bars were observed for an additional period of 1 yr. The results are indicated in the following tabulation and these data for six of the mortars are shown in fig. 17.

Cement	Expansion, % 364 days Bar 1	Bar 2	Bar 3	Bar 4	728 days Bar 3	Bar 4
330	315	311	129	122	326	327
336	25	24	14	16	19	21
337	75	70	39	37	48	47
338	54	59	20	25	28	31
339	371*	402*	42	40	90**	90**
340	171	160	44	43	208†	301
341	450*	391††	212	224	537‡	629‡‡
342	72	78	37	38	53	59
345	289	294	89	87	299§	271§
80-20	137	180	43	43	80	76
75-25	160	174	43	44	92	90
70-30	--	135	45	46	170	198

* 294 days after which bars broke.
** 588 days after which bars broke.
† 644 days after which bars broke.
†† 280 days after which bars broke.
‡ 457 days after which bars broke.
‡‡ 476 days after which bars broke.
§ 534 days after which bars broke.

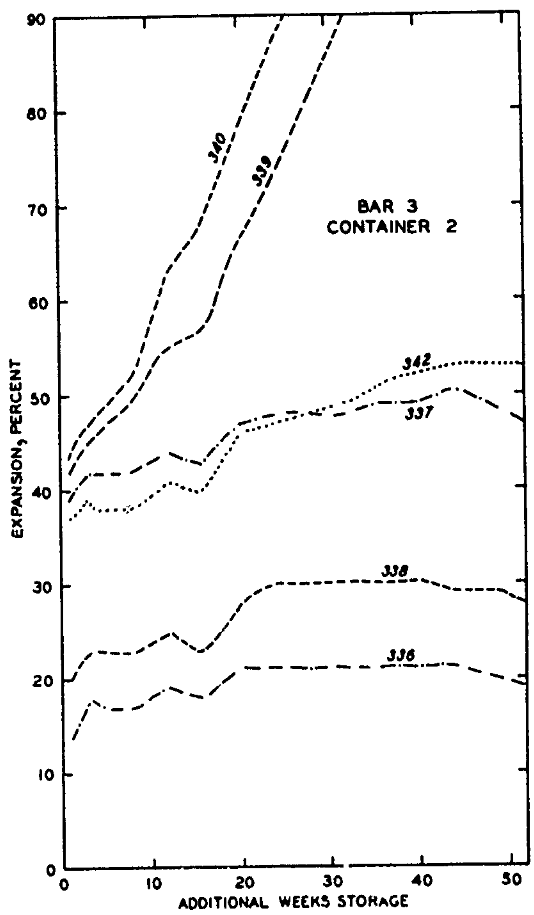


Fig. 17. Effect of additional storage after 1 yr in weaker sulfate solution

Comparison of results of mortar bar tests

52. For the purposes of comparing results of the two types of mortar bar tests, the average expansion at 364 days in the added-sulfate test (using round 1 data from the original test for cement 341) and average expansion at 364 days or when the bars were broken for bars 1 and 2 in the lean mortar bar tests are tabulated on the following page.

Cement	Expansion at 1 yr, percent x 10^3 Lean Mortar	Added Sulfate
330	313	136
337	72	162
338	56	172
339	386	436
340	166	690
341	420	748
345	292	295
342	75	203
336	24	89
80-20	158	245
75-25	167	216
70-30	135	200

53. With only a single exception (cement 340), the evaluation of the relative sulfate resistance of the eight portland blast-furnace slag ments was the same, ranked from the results of the test to 1 yr, whether determined by the added-sulfate or by the lean mortar bar method, as indicated below.

Lean Mortar Bars: Cement	Lean Mortar Bars: Expansion at 1 yr, % x 10^3	Added-Sulfate Mortar Bars: Cement	Added-Sulfate Mortar Bars: Expansion at 1 yr, % x 10^3
341	420	341	748
339	386	340	690
345	292	339	436
340	166	345	295
342	75	342	203
337	72	338	172
338	56	337	162
336	24	336	89

54. The fact that the relative positions of cements 337 and 338 are reversed is not regarded as significant. However, the difference in the position of cement 340 is considered significant; by one method it is clearly second and by the other, just as clearly fourth. Another anomaly is the position of the reference type II portland (330) relative to the portland blast-furnace slag cements. In the lean mortar bar test, expansion of the reference portland cement was 0.313% which puts it between the second and third place among the portland blast-furnace slag cements; in the added-sulfate test its expansion of 0.136% puts

it between seventh and eighth place.

55. The data on the blends of cement 339 with natural cement shown in the tabulation at top of page 34 suggest that the natural cement is an effective diluent for the expansion-producing characteristics of cement 339. Fig. 18 suggests that a 50 percent reduction in expansion would be obtained by between 18 and 25 percent replacement of cement 339 by natural cement depending on whether the estimate was based on lean mortar bar data or added-sulfate mortar bar data, respectively.

56. The additional expansion during a second year of exposure of lean mortar bars 3 and 4, which had low expansion at 1 yr due to deficient sulfate concentration in their exposure, yielded an apparently anomalous result in which the total expansion was inversely proportional to the percentage of cement 339 that was included.

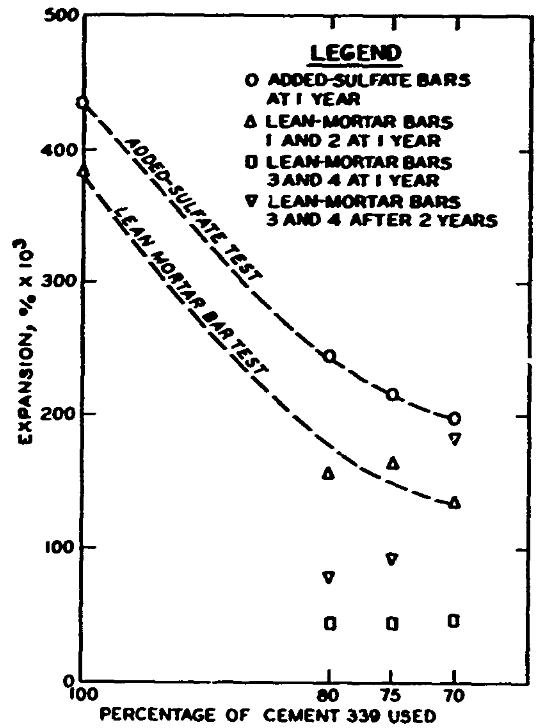


Fig. 18. Effect of blending natural cement with cement 339 on expansion in sulfate-resistance tests

57. In addition to comparisons based on total expansion at 1 yr, comparisons may be made between the cements based on the age at which they manifested the greatest expansion rate. In the lean mortar bar test there was little difference, since the shape of the curves (e.g. fig. 14) suggests an expansive reaction that began at approximately the same time and same rate for all bars, and then subsided at varying rates proportional to the expansive potential and the ultimate expansion of the cement. In the test with added sulfate, however, all bars having an expansion at 1 yr greater than 0.1 percent manifested a period of accelerated expansion followed by a plateau in which little additional expansion was recorded. Cement 338 is unique in that it had begun its rapidly expanding phase by the time it reached an age of 7 days and had achieved 90 percent of its ultimate (364 days) expansion before 21 days

age. Cement 341 (round 1 data) did not complete its expansion until 168 days. The period during which the average expansions passed 90 percent of their ultimate is indicated below:

Cement	Age, days, at Which 90% of Ultimate Expansion was Passed
338	14-21
337, 339, 342	56-84
340, 345	84-112
336, 341	140-168

Tests of concrete cylinders

58. The 3- by 6-in. concrete cylinders stored in water and in sulfate solution were tested for length change at 365 days age with the following results:

	Expansion of Concrete Cylinders, 365 days, percent x 10^3		Net Change Due to Sulfate
Cement	Water	Sulfate	
330	-20	+9	+29
337	-9	+1	+10
338	-33	+13	+46
339	-40	+9	+49
340	-23	-4	+19
341	-42	+3	+45
345	-20	-9	+11
342	-19	-4	+15
336	-48	-2	+46
80-20	5	-2	-7
75-25	5	-4	-9
70-30	-1	+13	+14

59. These results suggest that the storage in sulfate caused some expansion in all of the specimens except the 80-20 and 75-25 blends, but in no case was the magnitude of the expansion as great as 0.05 percent. Four of the concretes, those with cements 338, 339, 341, and 336, showed net expansions of between 0.045 and 0.049 percent.

Relation of Performance Test Results to Composition

Introduction

60. The report[10] on the study of the added-sulfate mortar bar test includes the following observations and conclusions:

a. Chemical limitations in current specifications appear adequate for the selection of portland cements that will produce sulfate-resisting concrete.

b. Such limitations make no allowance for improved portland cements that may have sulfate-resisting qualities without complying with the chemical limitations.

c. The added-sulfate test gives significant results in 28 days that are reproducible between laboratories and that discriminate between cements.

d. There is a good general relation between C_3A content of the cements and expansion of mortars but it is recognized that there are some other factors that influence sulfate resistance.

e. The LTS report[13] is quoted: "The fact that there are several striking exceptions to the relation between sulfate resistance and the C_3A content indicates that there is some unrecognized factor in the cement composition or in the manufacture of the cements that affects sulfate resistance."

61. In the discussion on pages 6-8 of MP 6-201[14] it was pointed out that the literature indicates that:

a. The mechanism of sulfate attack is predominantly that of the reaction of sulfates with hydrated calcium aluminates to form the more insoluble calcium sulfoaluminate with an accompanying increase in volume.

b. The sulfate resistance of a cement is increased by rapid cooling of the clinker which, presumably, causes part of the potential C_3A content to be poorly crystallized or included in the "glass" phase of the clinker. When C_3A is in the glass, it is much less susceptible to attack by sulfate. The expansion for one clinker of 11 percent calculated C_3A was reduced from 0.08 percent to 0.01 percent by rapid cooling of the clinker.

c. C_3A content of a cement may be estimated from chemical analysis, microscope examination, and X-ray diffraction. Calculations from chemical analysis permit no separation of well crystallized, poorly crystallized, or uncrystallized C_3A. Microscope examination differentiates C_3A present in crystals large enough to exhibit characteristic shape and behavior on etching from that not in such form. X-ray diffraction should discriminate degrees of crystallinity.

X-ray diffraction techniques

62. In view of the circumstances cited above, an attempt was made to develop data by the use of X-ray diffraction that could be employed to

relate composition and performance test results. To apply X-ray diffraction techniques to the study of the C_3A in a cement, or to the study of the presence, nature, and quantity of any constituent in a cement, it is necessary to establish that a given interatomic spacing (d, in angstrom units) corresponding to a given angle (degrees, 2θ) is characteristic of the substance under study, and then to apply one or more of several techniques to evaluate the intensity of X-ray diffraction apparatus.

63. In the case of C_3A, there is a spacing at 2.700 angstrom units that may be taken as diagnostic. This spacing was reported for pure C_3A in vol 5 of NBS Circular 539,[15] and was determined using tungsten as an internal standard, the results being corrected on the basis of the precisely known lattice constant of tungsten. The cumulative maximum error in these values is described at ±5 in the last significant figure.

64. There are four principal procedures for evaluating intensity of X-ray diffraction by a given sample when exposed at the selected angle; two of these involve determining the peak height in counts per second, two involve determining the integrated area under the peak. Each pair of procedures includes one in which the height or area is taken from the automatically recorded chart and one in which the height or area is determined from electronically scaled measurements of intensity.

65. The results given in the tabulation on page 25 of the first report for "Counts/sec 2.70 Å peak" were obtained by electronic scaling in triplicate at each of three locations on the surface of a sample. Background was calculated from a straight line drawn between 20 and 40 deg 2θ and subtracted from the mean of nine scalings to give the value reported for each cement.

66. The work being done by the X-ray diffraction group at the Portland Cement Association Research Laboratories includes determinations of integrated areas under peaks as automatically drawn on the recorder charts. Theoretically, a more desirable procedure would be to obtain electronically scaled intensity values at the angle corresponding to the peak apex and at smaller and larger angles, plot a trace from these values, and determine the integrated area under the plotted trace. Such a procedure would be rather difficult for the 2.700 Å peak of C_3A in cement because of the interference

of peaks due to other components at rather closely located angular positions both somewhat less and somewhat more than that corresponding to 2.700 Å.

Diffraction data on portland blast-furnace slag cements

67. As stated above, the X-ray diffraction results for the portland blast-furnace slag cements given in the first report were based on electronically scaled peak heights. Automatically recorded charts for the portland cement clinkers corresponding to these cements are available. These charts were examined to discover whether area information would contribute to a better evaluation of the C_3A story on these clinkers.

68. Diffraction charts of all of the portland blast-furnace slag cement clinkers with enough C_3A to scale--that is, all but cement 336--had been run at the fastest paper speed in the region 28 to 37 deg 2θ, at 49 kvp, 16 ma, using copper radiation filtered through two layers of nickel foil, takeoff angle 4 deg, 3 deg beam slit, MR Soller slit, 0.1 detector slit, range 3, time constant C. (If such a procedure were to be repeated, the 0.2 detector slit would be used.) The regions from 29.50 to 30.50 2θ and from 32.75 to 34.25 2θ were traced and superposed, using the scales of the chart paper as guides to align each tracing. This gave superposed tracings of the C_3S peak at 2.97 Å and the C_3A and aluminoferrite peaks at 2.70 and 2.65 Å. The curves were examined to see whether they contained information that might explain the anomalies of the positions of 339 which was second or third in expansion but fifth in scaled C_3A intensity; of 342 which was fifth in expansion and third in scaled C_3A intensity; and of 345 which was third or fourth in expansion with a scaled C_3A intensity like that of 339. The C_3A curves and the C_3S curves were compared by eye with respect to area and to sharpness, assuming that more area meant more of the substance and a sharper peak meant better crystallization. Bogue[16] concluded that "crystalline C_3A is less resistant to sulfate attack than a glass rich in C_3A, but crystalline C_4AF is more resistant than a glass rich in C_4AF. Hence in high A/F clinkers, sulfate resistivity is benefited by rapid cooling (high glass), whereas in low A/F clinkers, sulfate resistivity is benefited by slow cooling (low glass." The Al_2O_3/Fe_2O_3 ratios of all the clinkers are shown in table 9. The slag patterns were reexamined, but no new light was produced. Averages,

main aluminoferrite and aluminate peaks, and the C_3S peaks at 2.97 Å were computed from the values for 2θ read from the charts (table 10).

Discussion of results

69. The five cements that had clinker contents in the range from 55 to 60 percent may be compared on the assumption that expansion results were affected equally by the slag content. Curves for these five are shown in fig. 19 and ratings by other means in the upper portion of table 11. From these curves it appears that:

a. The height, area, and breadth of the bulge at the location of the main C_3A line is far greater in the curve of 342 than in that of any of the rest.

b. Cement 345 is second in height, area, and breadth of this feature, but is closer to the group which includes 339, 338, and 337 than to 342.

c. There is much less spread among the curves of the C_3S peak at 30 deg 2θ (2.97 Å). Cements 337 and 339 are quite similar, but 339 has less area. Cements 342 and 345 are quite similar, with 342 higher and broader. Cement 338 is the lowest.

From table 11 it appears that both ways of calculating C_3A and the X-ray scaled intensities failed to sort out these cements in the order of their expansion. The relative amounts of C_3A from fig. 19 ranked the cements that were in positions 2, 4, and 5 in expansion in these same positions, and it is worth noting that 339, with the highest expansion, had the best crystallized C_3A, while

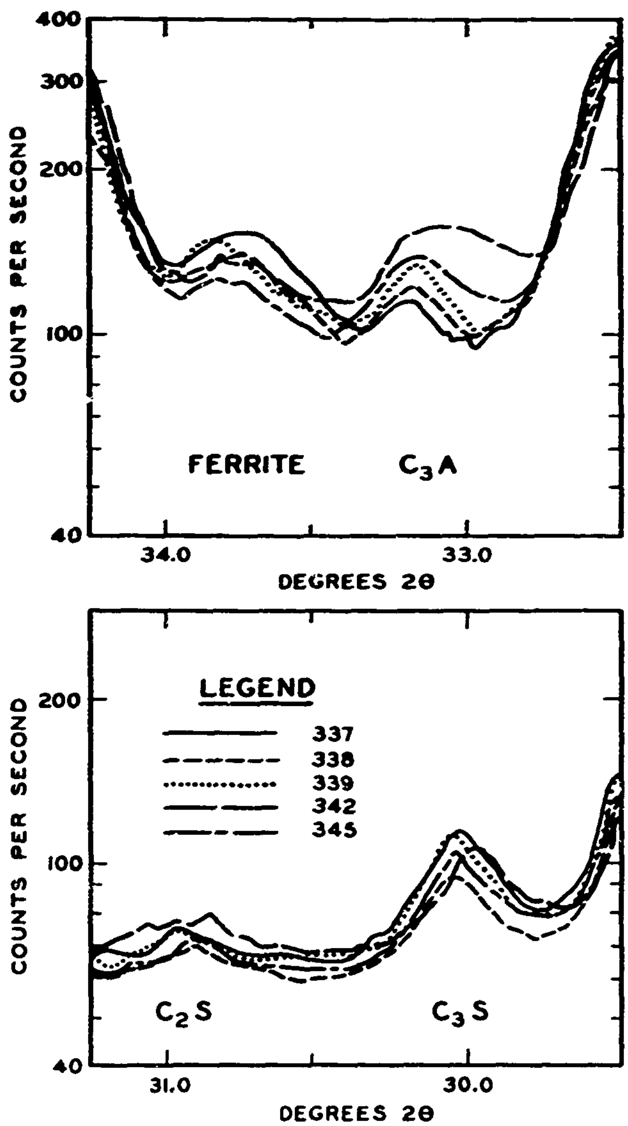


Fig. 19. X-ray diffraction traces for five portland blast-furnace slag cements

342, which had much the most C_3A, had the least well crystallized C_3A. Cement 342 contained an interground air-entraining agent; the report of the Working Committee on Sulfate Resistance[10] indicated that air-entrainment does not affect results in this test.

70. Fig. 20 shows the curves for the five cements that developed the greatest expansion (340, 339, 341, 345, 342). The lower portion of table 11 compares various ways of rating them. Cements 339 and 342 are anomalous by the standard method of calculation and by the X-ray intensity measurements, less anomalous by Swayze's method of calculation,[12] which came nearer to sorting these five cements in order of expansion than any other way tried. Fig. 20 suggests:

a. Cements 340 and 342 had most C_3A; 342 had more than 340 but it was less well crystallized and less efficient in causing expansion. Cement 340 had least, and the least well crystallized C_3S in this group, while 342 had the second most. Either or, more probably, both of these facts suggest why 340 expanded more than 342. The 8 percent difference in clinker content between the cements is probably not important, since 342 also expanded less than 345 and 339 in the group with comparable percentages of clinker.

b. The most important feature recognized in the X-ray pattern of 339 is the well crystallized nature of the C_3A.

c. Cements 341 and 345, although they differed in clinker content and expansion, had about the same expansion per

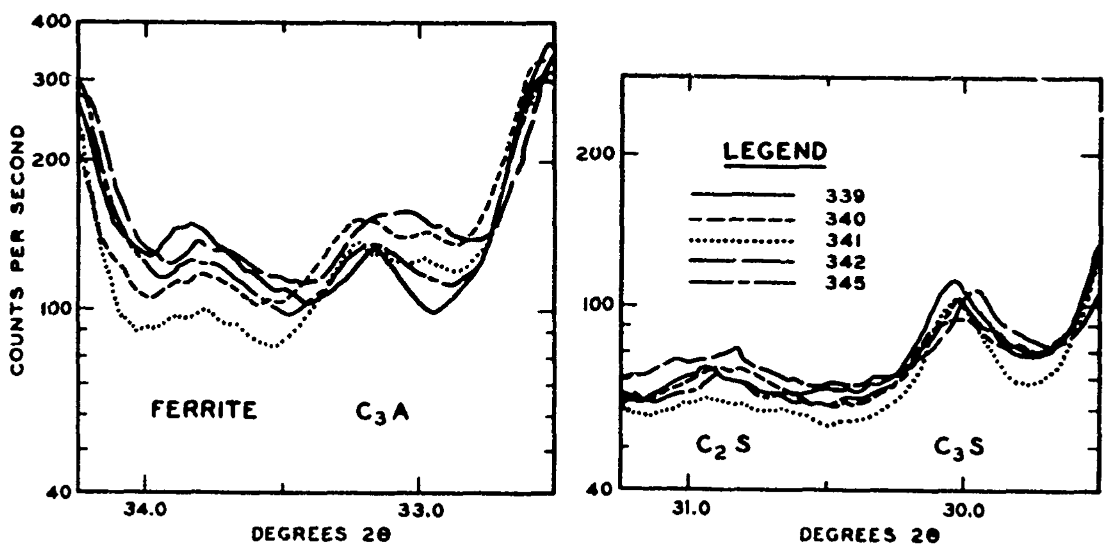


Fig. 20. X-ray diffraction traces for the five portland blast-furnace slag cements that developed greatest expansion

unit of clinker (table 12), which is in agreement with their relative positions in C_3A and C_3S contents (table 12, fig. 20).

71. Table 12, which summarizes the rankings for all eight cements, suggests that:

a. Either a fairly large amount of not very well crystallized C_3A or a smaller amount of well crystallized C_3A may produce large expansion in this test (340, 339).

b. If there is a large amount of not very well crystallized C_3A, its effect may be cancelled in part by a large amount of C_3S (342 versus 340).

c. Well crystallized C_3A is more important in producing expansion in this test than well crystallized C_3S in preventing it (338).

This approach gave four right answers in seven on amount of C_3A alone. It gave two possible explanations of why 340 expanded more than 342 (difference in C_3S content; difference in crystallinity of C_3A). It also gave a reason why 339 had such high expansion (best crystallized C_3A of any in the group).

72. Fig. 20 was prepared because the curves for 342 showed its peaks were offset to lower angles of 2θ than the rest of the clinkers, suggesting that the specimen surface was not plane. It has been observed that: (a) C_3S peak locations are quite reproducible from one cement or clinker to another; (b) the location of the main aluminoferrite peak around 2.65 Å varies from cement to cement in patterns where other evidence indicates that the specimen was plane and the apparatus in alignment; (c) there was some evidence of variation from cement to cement in the location of the main C_3A peak. In this group of clinkers, five presumably good observations of the location of the aluminoferrite peak in the C_6A_2F range were available (table 10); the mean is d = 2.6518 Å. The mean value found in six observations of the 2.97 Å peak of C_3S was 2.9740 Å; the mean for six observations of the main aluminate peak was 2.6970 Å. The last value may be compared with the previously cited NBS result for pure C_3A of 2.700. The cumulative maximum error in the NBS values is described as ±5 in the last significant figure. In previous comparisons of WES and NBS results, differences of about this magnitude, 0.003 Å, have been observed. The point of this discussion is not the accuracy of the results, but the observations given below.

a. Omitting 339, where the aluminoferrite composition is

presumably different, and 342 as a less perfect specimen, there were five determinations in the C_6A_2F range, yielding a mean of 2.6518 and a standard deviation of 0.00132.

b. The six values for the C_3S peak gave a mean of 2.9740, with a standard deviation of 0.00161.

c. Assuming a constant coefficient of variation of the three determinations shown in table 10, the expected value of standard deviation for the main aluminate peak should lie between the values found for the other two. This is not what happened; the aluminate peak gave the largest standard deviation, 0.00210. For the number of degrees of freedom involved, two standard deviations cannot be said to differ significantly unless their ratio exceeds about 2.5 to 1; the ratios for the standard deviations under discussion are 1.6 to 1 and 1.3 to 1. The coefficients of variation are: for the aluminoferrite, 0.050 percent; for the C_3S peak, 0.054 percent; for the aluminate, 0.078 percent. All are very low; thus, the data indicate that reproducibility is adequate. While the observed difference in standard deviation between these measurements of the position of the aluminate peak and those for the aluminoferrite and alite (C_3S) is not statistically significant, consideration was given to the question of why such a difference might actually exist.

d. The bulk of the C_3S may be assumed to have formed at a higher temperature than the aluminoferrite or the aluminate; temperatures in the kilns below its temperature of formation but above the temperature of the cooler should give it an opportunity to anneal. It is difficult (apparently almost impossible) to make glasses of aluminoferrite compositions because they tend to crystallize during quenching. It is possible to make glass of the C_3A composition. As a speculation, perhaps the C_3A in these clinkers did not have time to crystallize and anneal as well as the aluminoferrite and C_3S because it crystallized later. Figs. 19 and 20, however, do not offer clear support for this idea in the comparison of the C_3A and aluminoferrite peaks.

e. Yannaquis[17] reports subsidiary peaks in the pure beta-C_2S pattern between the very intense peak at approximately 2.75 Å and the location of the C_3A peak at 2.70 Å. He does not believe that the C_2S of clinker is pure beta C_2S, but believes that it is a compound (belite) with substitutions that raise its symmetry and incidentally diminish or abolish the intermediate peaks between 2.75 and 2.70 Å. His arguments are plausible, but perhaps less thoroughly documented than those of Jeffrey[18] on the differences between pure C_3S and alite, the substituted C_3S of clinker. There is, therefore, some doubt about how to interpret the very minute peaks at about 33 deg 2θ in the patterns of 337 (fig. 19), 340, 342, 341 (fig. 20). They may be subsidiary silicate

peaks related to C_2S, or they may represent calcium aluminate with substitutions, or neither. In 337, 341, and 340, the main peaks near the 2.70-Å location (33.15 deg 2θ) are at slightly higher angles than the single peaks of 339, 345, 337, 338; perhaps the first three represent calcium aluminate with substitutions.

f. It seems probable that the calcium aluminate phase of clinkers and cements may vary in composition from clinker to clinker. The aluminoferrite phase has been demonstrated to vary in lime, alumina, and iron content, and can contain manganese or magnesium, or both. It is still to be determined whether C_3S in cement always contains aluminum and magnesium, or whether it does not tolerate other substitutions. The vagaries of position of C_2S peaks in our patterns (e.g. figs. 19 and 20) have reinforced Yannaquis' idea that it, too, is a substituted compound. Why should C_3A be different from the rest? A sodium calcium aluminate was described some years ago.

73. In future work on diffraction patterns of cements, the possibility of sorting out different aluminoferrites by the location of the main peak should be considered, and an effort made to sort the X-ray data using the Al_2O_3/Fe_2O_3 ratio to see whether the grouping stands up. It may be possible to sort aluminates into some kind of a grouping, probably related to substitution, since the reason for the larger standard deviation of the C_3A peak in these data may be that more than one aluminate was present. Observations should be continued of the constancy or variation of C_3S peaks that are not interfered with by peaks of other constituents to determine whether C_3S is a constant entity as measured by diffraction, and to learn where the peaks really are. Further comments on some of these matters are given in the discussion of Nurse.[19]

PART V: RESISTANCE TO NATURAL WEATHERING

Specimens, Exposure, and Tests

74. As noted in paragraph 25 of the first report, six 3-1/2- by 4-1/2- by 16-in. beams were made from each batch of the 12 test mixtures of concrete and moist-cured to an age of 14 days. Then three beams from each batch were installed on the WES freezing-and-thawing exposure rack at Treat Island, Maine, and the other three were installed on the WES sea water exposure rack at St. Augustine, Florida. The 108 specimens for Treat Island were installed in May 1956; those for St. Augustine were installed in August 1956. Those at St. Augustine have been inspected and tested biennially, and those at Treat Island have been inspected and tested annually since 1956. The relative dynamic Young's modulus of elasticity of each specimen was determined on each inspection, and the results are given in table 13. These data were expected to indicate (a) the susceptibility to sulfate attack of the beams exposed to warm sea water, and (b) the resistance to freezing and thawing of the beams exposed at Treat Island.

Results of Exposure of Specimens at Treat Island

Field observations

75. The beams were installed on the rack at Treat Island with a 3-1/2- by 16-in. surface up, and were held in place by a 2- by 4-in. wood strip 4 in. long laid flat on top of each specimen perpendicular to the long dimension of the specimen at about its center. Therefore, on the top surface of each specimen, as installed, two areas each about 3-1/2 by 6 in. were exposed on either side of the wooden tie-down. Visual inspection of the specimens during the summer of 1957 revealed the development of surface scaling. The scaling was confined to that portion of the finished top surface adjacent to the wooden tie-down. The scaling had affected all specimens made with portland blast-furnace slag cements and was greatest on those made with cement 336, least on those made with cement 341. In 1958 the manner of attachment of the wooden tie-downs was changed so that

thereafter they did not touch the surfaces of the specimens.

76. In the summer of 1959 the specimens were examined by Dr. W. C. Hansen and Mr. Clayton L. Davis, both of the Universal Atlas Cement Division, U. S. Steel Corporation. Mr. Davis addressed the following comments to WES:

> The appearance of the specimens made with portland blast-furnace slag cement was compared to the control specimens made with Type II portland cement. Although there is no decrease in %E, which indicates that the specimens are not suffering any internal distress, there is far more surface scaling on the portland slag specimens than we would expect for concrete containing 6 percent of entrained air.
>
> In the field it is typical for portland blast-furnace slag cement, Type IS, to require considerably more air-entraining admixture than under parallel conditions with portland cement. Also, in the manufacture of Type IS-A cement it is necessary to add more air-entraining addition than with Type IA cement.
>
> In preparing the concrete batches from which the Type II portland cement and portland slag cement specimens were molded for the Treat Island exposure, you added the following quantities of air-entraining admixture (ml/bag) to obtain air content of 6.0 ± 0.5 percent:

	Type II Cement	Type IS Cements							Type IS-A Cement
		337	338	339	340	341	345	336	342
AEA ml/bag	96	62	75	75	50	50	66.7	67	50

> You will note that considerably more AEA was used in the Type II portland cement than in Type IS cement which is just the opposite of typical field experience. Also, three of the cements required 50 ml/bag even though one of the cements was Type IS-A.
>
> Since the surface scaling is definitely more severe on the portland slag cement specimens than on the Type II portland cement specimens, and in view of the relative amounts of AEA that were used, I wonder if the hardened portland slag concrete contains significantly less entrained air than Type II portland cement concrete. I would like to suggest that some time soon one typical beam from each of the 12 groups [mixtures] of beams be selected and an estimate of the percentage air entrainment be made microscopically. I can, with your premission, arrange to have the air content determination made at the PCA Research Laboratories if you would send them the specimens.

Air content of beams

77. Available data. The data presented by Mr. Davis indicate

that: (a) All the portland blast-furnace slag cement concretes required significantly less admixture to produce the specified air content than did that made with the reference type II cement. (b) Two of the nonair-entraining type IS cement concretes required no more admixture than did concrete made with the air-entraining portland blast-furnace slag cement (342).

78. The anomalous air-entraining admixture demand by the air-entraining cement concrete cannot be confirmed by other available data. When tested for air in mortar, cement 342 was found to contain 15.9 percent air, while the air content of the six commercial nonair-entraining portland blast-furnace slag cements ranged from 3.8 to 5.9 percent. When tested in 6-in. aggregate concrete, 18 ml/bag of AEA was required for the air-entraining cement, while the other six commercial cements required from 37 to 50 ml/bag.

79. Selection of specimens for tests. In accordance with the suggestion made by Mr. Davis, a group of 12 specimens was selected for study of air content, and returned to the WES laboratory in September 1959. The specimen selected from each of the 12 groups of nine beams was the one showing the greatest development of surface scaling. The basis for this selection was to insure that if there were a relation between scaling and inadequate air entrainment, each group presumably would be represented by the specimen having the poorest air void system, should there be a within-group difference.

80. It can be observed from table 13 that the specimens selected as showing greatest scaling were not generally those also showing lowest relative modulus of elasticity; in two cases they were those showing the highest relative moduli, in two cases they showed the lowest, and in the remaining eight cases they were intermediate.

81. Scaling rating of specimens. The specimens were examined and rated in accordance with the degree to which they showed scaling. Least scaling was present on specimen 136 (330, type II) and most on specimen 2 (336, experimental high-slag content, high MgO slag, portland blast-furnace slag cement). The rating of the 12 specimens in order of amount of scaling was:

Rating in Amount of Scaling	Specimen No.	Cement
(1) least	136	330 (type II)
(2)	94, 170, 190	341, 80-20 blend, 75-25 blend
(3)	110	342 (IS-A)
(4)	156	345
(5)	58, 26	339, 337
(6)	80, 40	340, 338
(7)	216	70-30 blend
(8) most	2	336 (exp)

82. Air content tests. The 12 specimens were sawed as indicated in fig. 21 and the central 1-in. thick slice was forwarded (in 3 slabs) for testing at the Portland Cement Association Research Laboratories, Skokie, Illinois. The test results were reported by Mr. J. E. Cox (file 3.3.9)

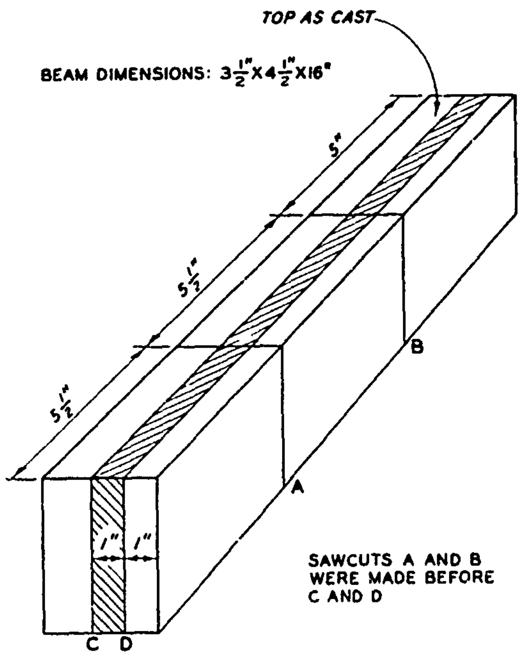


Fig. 21. Preparation of specimens for air content study

to Mr. Paul Klieger, Manager, Field Research Section, who furnished them for use in this report. The three slabs from the center slice of each specimen were separately examined by the linear-traverse method. The results are given in table 14.

Results and discussion of results

83. The compilation of results of earlier pertinent tests and of the PCA tests given in table 14 reveal the following relations:

a. The air content of the hardened concrete was found to be, in general, about 0.5 percent less than the reported air content of a sample of the same batch tested in the freshly mixed condition (fig. 22).

b. The batch with the highest and the batch with the lowest air contents when freshly mixed (6.5 and 5.5, respectively) also had the highest and lowest air contents when tested in the hardened condition (6.3 and 4.0, respectively).

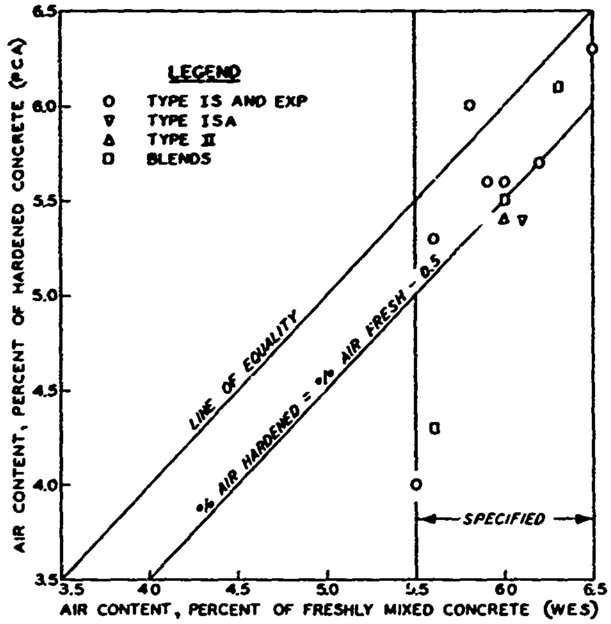


Fig. 22. Relation of air contents of freshly mixed and hardened concretes

c. The concrete made using air-entraining cement (342) showed the most uniform hardened air content among the three center-slice specimens tested (range 0.38 percent).

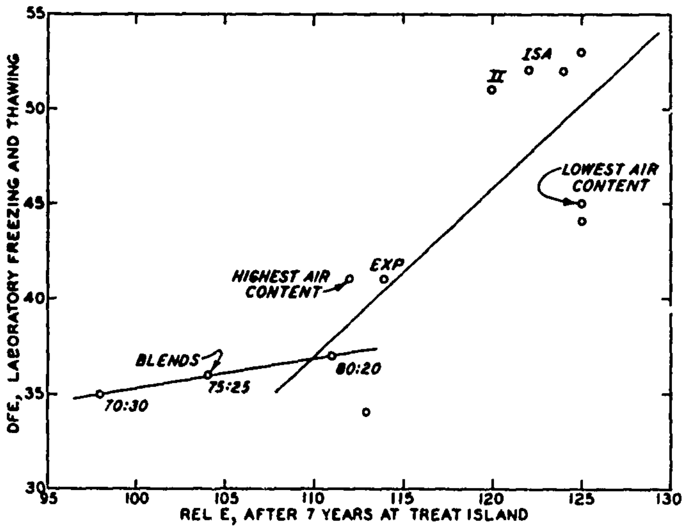


Fig. 23. Relation of resistance to freezing and thawing as indicated by laboratory and field tests

d. The concrete with lowest air content (5.5 percent when freshly mixed, 4.0 percent when hardened) made with cement 337 has not shown lower resistance to freezing and thawing than the average of the group as a whole.

e. A relation exists between the resistance of these concretes to freezing and thawing as measured by laboratory testing and as measured by exposure at Treat Island (fig. 23). Either the relation is curvilinear or there

are two linear relations, one for the mixtures made with blends of cements and another for the other mixtures.

f. There is no relation between level of air content and resistance to freezing and thawing, as indicated by relative modulus of elasticity, for these concretes, either on the basis of the air content measured when the concrete was freshly mixed or hardened.

Results of Exposure of Specimens at St. Augustine

84. The 108 specimens exposed at St. Augustine in 1956 were tested in 1958, 1960, 1962, and 1964. All specimens except one have shown relative moduli of elasticity higher than at the time of installation on all subsequent testing; the values in 1964, for example, range from 93 to 146 percent of those at installation (see table 13). The six specimens showing 1964 relative moduli of 110 percent or less percent include: (a) the three specimens from round 3 of the concrete containing the experimental high-slag cement 336, (b) one specimen from round 2 of the cement 345 concrete, and (c) two specimens from round 3 of cement 338 concrete. The detrimental effects of exposure at St. Augustine are generally confined to the development of manifestations of lack of sulfate resistance. On this basis it would be expected that if a differentiation were to develop among these concretes, those of lowest sulfate resistance would display the lowest relative moduli. Cements 339 and 340 would be expected to fall in this category based on results of laboratory investigations. The 1964 test results for concrete made with cement 340 range from 115 to 131 percent relative modulus; those for concrete made with cement 339 range from 112 to 136.

85. These results suggest either of two interpretations:

a. The duration of the exposure to sea water has not yet been long enough to allow the development of potential sulfate attack on these specimens of relatively good quality concrete so that useful differentiation can be made, or

b. The characteristics of the concrete are such as to preclude the development of sulfate attack and consequent confirmation of the indications of the laboratory tests. In connection with this alternative, it is noted that the laboratory indications were developed primarily from observations of the cements themselves, pastes, and silica-sand mortars while the concrete specimens contain

crushed limestone coarse aggregate. Stolnikov[20] has reported that, in the presence of calcium carbonate, tricalcium aluminate does not hydrate to the normal calcium aluminate hydrate (C_3AH_6), which is the product with which sulfate ion generally reacts to form calcium sulfoaluminate, with an increase in volume. He suggests that in the presence of calcium carbonate, the C_3A reacts to form, on the surfaces of the carbonate aggregate particles, the product calcium carboaluminate, which has a beneficial effect on paste-aggregate bond.

PART VI: ADDITIONAL DATA ON MATERIALS AND CONCRETE MIXTURES

Chemical Composition of Slags

86. Chemical data on the eight samples of slag furnished as representative of that used in the manufacture of the portland blast-furnace slag cements were presented and discussed in paragraphs 6 and 7 of the first report. Subsequent to the issuance of the first report, a paper by Taro Tanaka[21] gave data on the relation of $CaO:SiO_2:Al_2O_3$ proportions of slags to the compressive strength developed in slag-sulfate cements. Tanaka showed that the optimum composition for maximum compressive strength in these products was: SiO_2, 31 to 33 percent; Al_2O_3, 18 to 19 percent; and CaO , 49 to 50 percent. The chemical composition of the eight slag samples was computed to 100 percent for SiO_2, Al_2O_3, and CaO. These values are plotted on a portion of a triangular diagram (fig. 24) on which the optimum referred to by Tanaka is also shown. The eight slags in this study have values of SiO_2 from 36 to 42 percent, Al_2O_3 from 10 to 14 percent, and CaO from 46 to 51 percent, or somewhat higher SiO_2 and somewhat lower Al_2O_3 than suggested as optimum by Tanaka for the cement compositions that he studied.

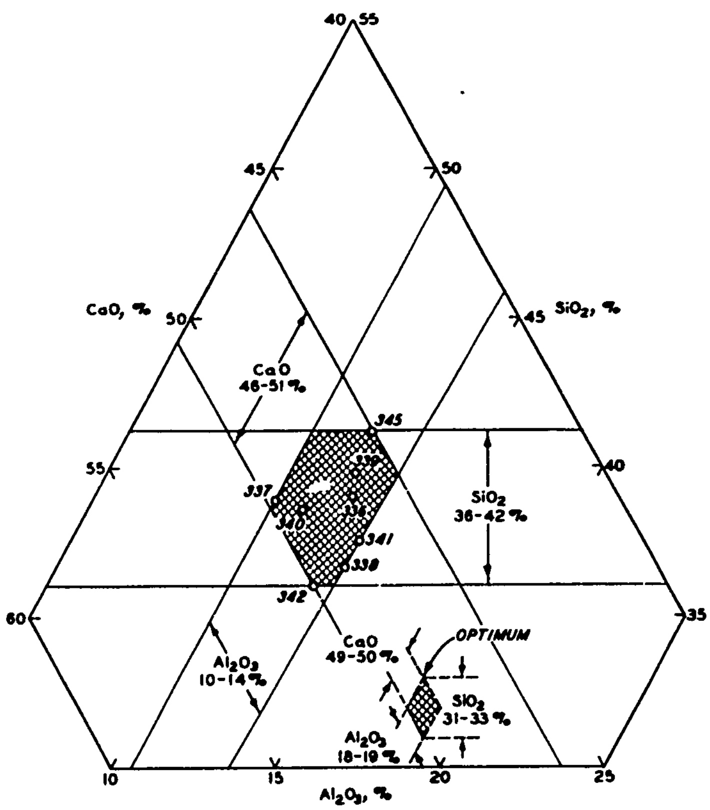


Fig. 24. $CaO:Al_2O_3:SiO_2$ proportions of slags used in portland blast-furnace slag cements and "optimum" zone as determined by Tanaka[21] with locations of slags studied shown

87. Also subsequent to the issuance of the first report, additional information has become available on the use of slags of higher

magnesia content than is permitted by existing specifications. One such report,[22] translated and issued by WES, discussed a slag with approximately 32 percent MgO found to have good hydraulic properties, no periclase, and no abnormal expansion in the autoclave test.

Alkali-Aggregate Reaction

88. Results of tests for alkali-aggregate reaction of mortar bars made with pyrex glass aggregate to an age of 168 days are given in the first report (table 14, fig. 11, and paragraph 47). It was noted that at this age the expansion of bars with the reference type II cement, which had an alkali content of 0.68 percent expressed as Na_2O equivalent, was 0.104 percent, whereas that of all of the bars made with portland blast-furnace slag cement and blends of cement 339 and natural cements was less than 0.050 percent. The exposure of these bars was continued to an age of 728 days; the results are given in table 15. In all cases, except for the blends of portland blast-furnace slag cement and natural cement, the expansion increased with increasing age; that of the reference type II portland was 0.127 percent at the ultimate age and that of the portland blast-furnace slag cement having the highest alkali content (0.75 percent Na_2O equivalent) was 0.055 percent. Fig. 25 shows the

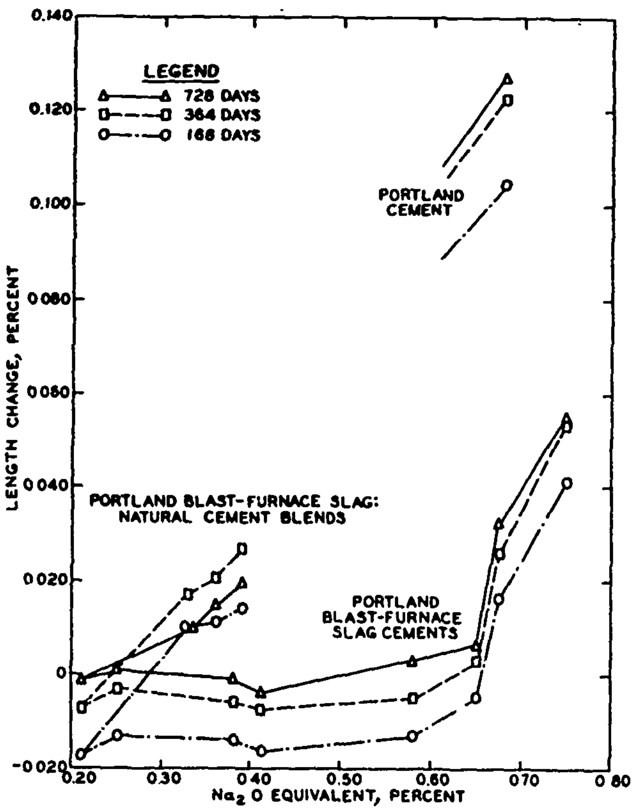


Fig. 25. Relation of expansion of pyrex glass aggregate mortar bars to soda equivalent of cements.

relation between the indicated length change at 168, 364, and 728 days and the alkali content of the cements and blends that were used. The indication from this figure is that, while 0.60 percent soda equivalent is an appropriate level of alkali content for separating portland cements that may be expected to produce excessive expansion when used with highly reactive aggregates from those that may be expected not to do so, a similar limit for portland blast-furnace slag cement might well be established at a considerably higher point, perhaps somewhere in the vicinity of 1.20 percent soda equivalent.

89. One of the reasons for continuing the exposure of the bars to an age of 728 days was to investigate the possibility that the alkali content of the slag might be released at later ages and thus its effect would only show up during such additional exposure. While the expansion continued to increase with age, the magnitude of the increase was not significantly greater for the portland blast-furnace slag cement bars than it was for the bars made with the reference type II portland cement. The blends of cement 339 and natural cement indicate a possible similar relation to that of the portland cement. The portland blast-furnace slag cement constituent of these cements had the lowest alkali content of any of the blast-furnace slag cements and the natural cement had a higher alkali content than did the portland blast-furnace slag cement with which it was blended, these values, expressed as soda equivalent, being 0.21 and 0.80. The indications from the graph are that the presence of the slag did not serve to suppress the activity of the alkali derived from the natural cement constituent of the blends as contrasted with the behavior of the slag. Take the case, for example, of cement 345 where apparently the presence of the slag did serve markedly to reduce the effectiveness of the alkali in the portland cement clinker constituent in producing expansive reaction.

Length Change and Thermal Coefficient

90. Paragraph 22 of the first report states that six 2- by 2- by 11-in. prisms were made from each batch, three for testing for drying shrinkage at 50 percent relative humidity, and three for testing for expansion

caused by continuous immersion. Results to the 180 days age were reported, and it was stated that at the 1-yr age the immersed specimens would be tested for linear coefficient of thermal expansion. These tests were made, and in addition, at an age of 28 $\pm$ 2 months, all the bars were again tested for length change and for dynamic Young's modulus of elasticity and weight. The results are given in table 16.

91. It will be noted that the shrinkage specimens continued to show slight additional average shrinkage from 180 to 364 days and to 28 $\pm$ 2 months. At 28 $\pm$ 2 months, these specimens were found to weigh on the average from 0.11 to 0.22 lb less than the comparable specimens that had been soaked. The expansion specimens showed generally negligible average length changes between 180 and 364 days age. At 364 days they were tested for linear coefficient of thermal expansion with average results from 4.05 to 4.40×10^{6} per degree Fahrenheit. The dynamic moduli at 28 $\pm$ 2 months varied from 4.2 to 5.6×10^{6} psi for the shrinkage specimens and from 6.6 to 7.1 for the soaked specimens.

92. Between the 1-yr age at which the bars were tested for thermal coefficient, and the 2-yr age at which they were again tested for length change, many of the bars underwent relatively large length changes--from a shrinkage of 0.196 percent to an expansion of 0.020 percent. These changes generally affected groups of three bars similarly, but not groups of nine representing a given concrete mixture made using a given cement. The tendency to show large shrinkage appears to have affected both of the two sets of three bars tested for thermal coefficient on a given day, but not to have affected other pairs of sets of three tested on other days. In two cases only one set of three bars was tested for coefficient of expansion on a given day. In one of these two cases the three bars showed shrinkage thereafter of 0.072, 0.171, and 0.196 (average shrinkage 0.146 percent); in the other case the bars showed expansions of 0.015, 0.016, and 0.017 (average expansion 0.016 percent). On 17 different days, two sets of three bars were tested for thermal coefficient; the subsequent length changes of these bars ranged from one case in which the two sets showed expansions of 0.015, 0.011, and 0.015 (average expansion 0.014) and expansions of 0.013, 0.006, and 0.006 (average expansion 0.008) to another case in which the two sets showed shrinkages of 0.084, 0.057, and 0.061 (average shrinkage

0.067) and shrinkages of 0.042, 0.051, and 0.051 (average shrinkage 0.048). Nothing in the records of the testing appears to suggest an explanation of the length change behavior of these bars during the period of subsequent immersed storage after having been tested for thermal coefficient. Their storage was continued to an age of 40 ± 2 months and additional tests for dynamic Young's modulus and length change were made. The computed moduli of elasticity were equal to or slightly higher than at 28 months in all cases except that of specimens with cement 345 for which the modulus increased from 7.0 to 7.5 x 10^6 psi. This concrete also showed the maximum shrinkage of the soaked specimens. The 40-month data by rounds, three specimens per round, for this cement are:

	Cement 345		
	Round 1	Round 2	Round 3
Length change, %	+0.007	-0.031	-0.137
Modulus, psi x 10^{-6}	7.5	7.5	7.4

93. Additional soaking between the ages of 28 and 40 months did not eliminate the discrepant length change relations noted at the 28-month age.

Strength and Elastic Properties

94. In the first report, fig. 5 on page 12 gave the relations of compressive strength development for ages up to [illegible] days. The curve shown for cement 336 was plotted incorrectly. A corrected curve and the other curves extended to include results of tests at [illegible] and 365 days are given in fig. 26.

Performance of Blends

95. The performance of one portland blast-furnace slag cement blended in three proportions with one natural cement was investigated as part of this program. Limited studies have been made by others of blends of portland blast-furnace slag cement and fly ash.[26,27] A recent publication "Proportioning Guide for Concrete Mixes Containing Fly Ash"[23] states: "Some Type IS cements have proved satisfactory with fly ash and others have not!" Information was requested on the basis for this statement and it was learned that it was inserted as a result of an expression of opinion that the performance of fly ash in concrete would not be

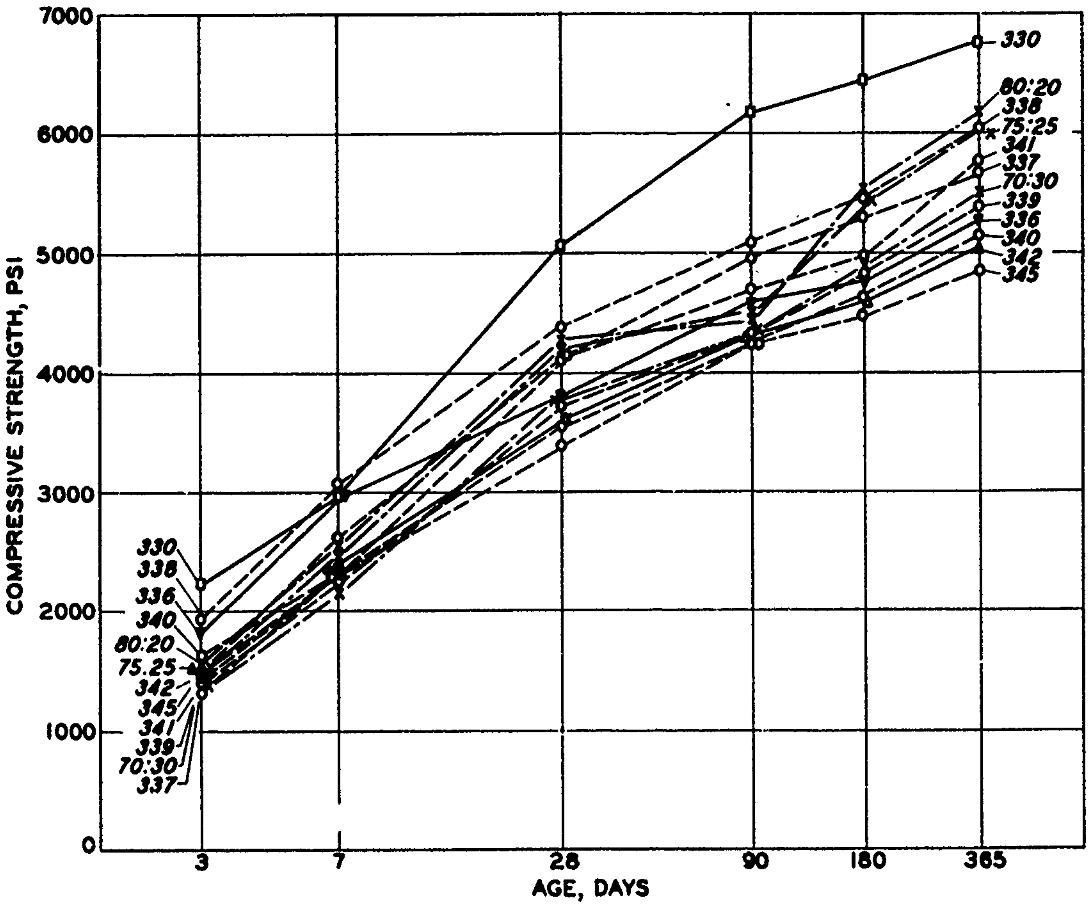


Fig. 26. Rate of development of compressive strength

satisfactory if used with a portland blast-furnace slag cement that contained close to the maximum allowable slag content of 65 percent. No test results are known to be available concerning the performance of concrete made using fly ash and a portland blast-furnace slag cement that contained close to the maximum allowable slag content of 65 percent. The work that has been done[26,27] involved use of a portland blast-furnace slag cement in which the slag constituent made up about 40 percent of the product. In this study it was found that the substitution of fly ash for 20 to 30 percent of the volume of either type IS or type IS(MH) cement in concrete mixtures will produce a reduction in compressive strength of from 30 to 45 percent at 7 days, 20 to 30 percent at 28 days, and from 15 to 35 percent at later ages. These strength reductions are in the same order as the percentages of cement replaced with fly ash, which indicates that the fly ash is not effectively utilized as a cementing material.

96. The results available early in 1956 when the first report was prepared appeared to justify the conclusions that:

- a. Portland blast-furnace slag cements complying with (then) current Federal and ASTM requirements may be considered essentially equivalent to type I portland cement.
- b. To insure that they possess the distinguishing qualities of type II portland cement, additional requirements regarding heat of hydration or sulfate resistance or both will need to be invoked.

97. The supplementary investigations, together with the completion of the studies in progress in 1956, provide a basis for the following conclusions:

- a. The additional data include none that require modification of the original conclusions.
- b. Concretes made with portland blast-furnace slag cements are not more adversely affected by early termination of moist-curing nor do they promote corrosion of embedded steel more than concretes made with the reference type II cement used in these tests.
- c. The precautions taken to achieve appropriate degrees of sulfate resistance of concretes made with portland cement may be expected to be entirely adequate when employed with respect to concretes made with portland blast-furnace slag cement.
- d. Resistance to natural weathering, involving the sulfate attack of a marine exposure or severe freezing and thawing or both, of concrete made using portland blast-furnace slag cements appears to be entirely similar to what would be expected of concretes of comparable properties made with portland cements.

LITERATURE CITED

1. U. S. Army, Office, Chief of Engineers, Standard Practice for Concrete. EM 1110-2-2000, 15 December 1963.

2. __________, Standard Guide Specifications for Concrete. CE 1401.01, August 1963.

3. U. S. Army Engineer Waterways Experiment Station, CE, Handbook for Concrete and Cement, with quarterly supplements. Vicksburg, Miss., August 1949.

4. Brady, F. L., The Corrosion of Steel by Breeze and Clinker Concretes. Dept. Sci. Ind. Research, Building Research, Special Report No. 15, 1930. "Concretes." Chemical Abstracts (10 September 1930), p 4371.

5. Otten, A. F., "Corrosion of iron in concrete containing boiler slag." Stroitel. Prom., No. 2 (1940), pp 59-61; Khim. Referat. Zhur., No. 8 (1940), p 138; and Chemical Abstracts (20 November 1942), p 7255.

6. "Slag cement." Chemical Week (19 January 1957), p 72.

7. "Unique type of cement reported in production." The Journal of Commerce (2 January 1957), p 12.

8. Ost, Borje, and Monfore, G. E., "Corrodibility of prestressing wire in concretes made with type I and type IS cements." Journal of the Portland Cement Association Research and Development Laboratories, vol 5, No. 2 (May 1963), pp 23-26. (Reprinted as PCA Research Bulletin 159.)

9. Lea, F. M., and Watkins, C. M., The Durability of Reinforced Concrete in Sea Water; Twentieth Report of the Sea Action Committee of the Institution of Civil Engineers. National Building Studies, Research Paper No. 30, Building Research Station, D.S.I.R.O., London, 1960.

10. American Society for Testing Materials, Working Committee on Sulfate Resistance, "A performance test for the potential sulfate resistance of portland cement." American Society for Testing Materials Bulletin, No. 212 (February 1956), pp 37-44.

11. Wolochow, David, "Determination of the sulfate resistance of portland cement." Proceedings, American Society for Testing Materials, vol 52 (1952), pp 250-266.

12. Swayze, M. A., "A report on studies of (1) the ternary system $CaO-C_5A_3-C_2F$, (2) the quarternary system $CaO-C_5A_3-C_2F-C_2S$, and (3) the quarternary system as modified by 5% magnesia." American Journal of Science (January and February 1946), pp 1-30 and 65-94, respectively.

13. McMillan, F. R., and others, "Concrete exposed to sulfate soils."

Long-Time Study of Cement Performance in Concrete, Chapter 5, Research Laboratories of the Portland Cement Association, Bulletin 30, Special Publication of American Concrete Institute, December 1949, 64 pp.

14. U. S. Army Engineer Waterways Experiment Station, CE, Comparison of Methods of Estimation of Tricalcium Aluminate Content of Portland Cement in Connection with the Evaluation of Potential Sulfate Resistance, by Katharine Mather. Miscellaneous Paper No. 6-201, Vicksburg, Miss., March 1957.

15. National Bureau of Standards Circular 539, Standard X-Ray Diffraction Powder Patterns, vol 5, 21 October 1955.

16. Bogue, R. H., Studies on the Volume Stability of Portland Cement Pastes. Portland Cement Association Fellowship Paper No. 55, National Bureau of Standards, Washington, D. C., December 1949.

17. Yannaquis, Nicolas, "Étude aux rayons X des silicates du clinker (X-ray studies of silicates in clinker)." Revue des Materiaux de Construction, No. 480 (September 1955), pp 213-228.

18. Jeffery, J. W., "The tricalcium silicate phase." Proceedings, Third International Symposium on the Chemistry of Cement, London (1952), pp 30-48.

19. Mather, Katharine, discussion of paper, "Phase equilibria and constitution of portland cement clinker," by R. W. Nurse. Chemistry of Clinker, National Bureau of Standards Monograph 43, vol 1 (1962), pp 34-35.

20. Stolnikov, V. V., "The selection, processing, and specifications of aggregates for concrete for large dams in the U.S.S.R." Transactions, Seventh International Congress on Large Dams, Rome, Italy, vol 1 (1961), pp 777-797.

21. Tanaka, Taro, "From blast furnace slag to cement." Part 3, Rock Products, vol 60 (October 1957), pp 163-164, 166, and 196.

22. Cirilli, Vittori, and Brisi, Cesare, "Ricerche sull'utilizzazione di scorie fortemente magnesiache nell'industria dei leganti idraulici (Researches concerning the utilization of slags with a high magnesia content in the hydraulic binder industry)." L'Industria Italiana del Cemento (September 1955). Translation by Jan C. Van Tienhoven, U. S. Army Engineer Waterways Experiment Station Translation No. 57-1 (February 1957).

23. Chicago Fly Ash Co., Walter N. Handy Co., and McNeill Brothers, Inc., Proportioning Guide for Concrete Mixes Containing Fly Ash. (No date.)

24. U. S. Army Engineer Ohio River Division Laboratories, CE, Investigation of Green Bag Portland-Pozzolan Cement Proposed for use in Concrete for Construction of Lock No. 2, Monongahela River. October 1952.

25. U. S. Army Engineer Ohio River Division Laboratories, CE, Third Interim Report of an Investigation of the Properties of Blended Cement Concretes; Greenup Locks and Dam Project. January 1957.

26. ________, Report of an Investigation of the Use of Fly Ash as a Partial Replacement for Portland Blast Furnace Slag Cement in Concrete. August 1960.

27. ________, Second Interim Report on the Effect of Added Hydrated Lime on Cement - Fly Ash Concrete and Mortars. April 1962.

Table 1

Comparison of Chemical and Physical Data on Reference Type II Cements Used in Basic Investigation (RC-330) and in These Tests (RC-376)

Component or Test	Reference Type II Cement 330	Reference Type II Cement 376
Chemical Data		
SiO_2, %	23.1	22.6
Al_2O_3, %	5.0	4.4
Fe_2O_3, %	3.9	3.9
CaO, %	61.1	63.1
MgO, %	2.8	3.0
SO_3, %	2.0	1.6
Na_2O, %	0.23	0.19
K_2O, %	0.69	0.58
Total alkalies as Na_2O, %	0.68	0.57
Insoluble residue, %	0.23	0.44
Loss on ignition, %	1.6	0.6
C_3A, %	7	5
Physical Data		
Heat of hydration, cal/g		
7 days	71	70
28 days	82	83
Specific surface (air permeability), sq cm/g	3590	3315
Normal consistency, %	24.6	24.6
Autoclave expansion, %	0.10	0.11
Time of setting (Gillmore), hr:min		
Initial	5:30	3:45
Final	8:00	6:00
Air content of mortar, %	8.8	5.2
Compressive strength, psi		
3 days	1745	1790
7 days	2665	2985
28 days	5140	5750

Table 2

Test Data on Aggregates

Test	Results
Fine Aggregate	
Bulk specific gravity, saturated surface-dry	2.63
Absorption, %	0.3
Mortar strength, %	
3 days	131
7 days	122
Grading range, cumulative % passing	
No. 4	99 ± 1.0
No. 8	88 ± 2.0
No. 16	70 ± 2.5
No. 30	48 ± 5.0
No. 50	25 ± 2.0
No. 100	5 ± 1.0
Fineness modulus	2.65 ± 0.04
Coarse Aggregate	
Bulk specific gravity, saturated surface-dry	2.70
Absorption, %	0.6
Soundness, loss 5 cycles, %	3.2
Abrasion loss, %	19.7
Flat and elongated particles, %	2.1
Grading range, cumulative % passing	
3/4-in.	99 ± 1
1/2-in.	66 ± 3
3/8-in.	33 ± 3
No. 4	0 to 3

Table 3

Effects of Early Termination of Moist-Curing on Strength and Modulus of Elasticity of Concrete Specimens

Cement Serial No. RC-	Type	7 days W*	7 days D*	28 days W	28 days D	90 days W	90 days D	1 yr W	1 yr D
				Compressive Strength, psi**					
376	II	4180	4050	5530	4620	6650	4360	7200	4650
337	IS	2400	2500	4160	3200	5060	3050	5700	3110
338	IS	2790	2750	4210	3680	4850	3900	5530	3690
339	IS	2440	2400	3790	3220	4550	3120	5420	3040
340	IS	2410	2510	3500	3140	4210	3400	5010	3390
341	IS	2440	2420	3680	2970	4670	3000	5240	3120
345	IS	2580	2560	3530	3420	4290	3700	4710	3510
342	IS-A	2610	2730	3760	3180	4540	3420	5160	3410
336	Exp	3390	3460	4540	4330	5180	4580	5910	4180
				Flexural Strength, psi**					
376	II	795	605	880	705	945	815	885	740
337	IS	625	460	890	600	910	680	955	645
338	IS	675	470	850	550	870	765	855	680
339	IS	575	465	800	580	865	630	940	630
340	IS	640	535	760	570	835	735	785	705
341	IS	600	505	795	600	815	720	795	630
345	IS	675	510	785	560	880	700	825	735
342	IS-A	675	500	815	560	900	710	875	665
336	Exp	820	540	945	640	960	690	950	750
				Modulus of Elasticity, psi**					
376				5.30	4.20			5.56	4.24
337				4.62	3.80			5.60	3.46
338				4.85	3.76			5.37	3.52
339				4.63	3.63			5.44	3.36
340				4.68	3.84			5.38	3.70
341				4.72	3.32			5.29	3.46
345				4.72	4.01			5.10	4.03
342				4.82	3.82			5.64	3.69
336				5.10	4.28			5.34	3.64

* W = moist-cured until time of test; D = moist-curing terminated at 3-day age.

** Each value represents the average of the tests on six specimens.

Table 4

Results of Corrosion Tests

Rusted Area	Age	Length and Nominal Depth of Cover											
		10 in., 1 in.						6 in., 3 in.					
		Cement 376		Cement 339		Cement 338		Cement 376		Cement 339		Cement 338	
		No.	Area	No.	Area	No.	Area	No.	Area	No.	Area	No.	Area
Laboratory Exposure													
Pinpoints	90	231	231	294	294	77	77	215	215	61	61	27	27
1/16-in.	days	53	212	32	128	13	52	10	40	2	8	0	0
1/8-in.		25	400	28	448	19	304	13	308	2	32	0	0
1/4-in.		3	192	3	192	1	64	1	64	0	0	0	0
		Total	1,035		1062		497		627		101		27
Pinpoints	365	300	300	149	149	104	104	145	145	68	68	11	11
1/16-in.	days	103	412	34	136	26	104	20	80	14	56	1	4
1/8-in.		31	496	18	288	1	16	0	0	1	16	0	0
1/4-in.		13	832	1	64	3	192	0	0	0	0	0	0
		Total	2,040		637		416		225		140		15
Sea-Water Exposure at St. Augustine, Florida													
Pinpoints	2 yrs	119	119	79	79	42	42	77	77	14	14	3	3
1/16-in.		24	96	15	60	6	24	2	8	--	--	1	4
1/8-in.		22	352	8	128	2	32	--	--	--	--	--	--
1/4-in.		6	384	3	192	--	--	--	--	--	--	--	--
		Total	951		459		98		85		14		7
Pinpoints	4 yrs	310	310	281	281	121	121	188	188	64	64	53	53
1/16-in.		130	520	34	136	9	36	39	156	1	4	2	8
1/8-in.		77	1,232	25	400	10	160	15	240	--	--	--	--
1/4-in.		58	3,712	3	192	2	128	8	512	--	--	--	--
1/2-in.		14	3,584	2	472	--	--	--	--	--	--	--	--
3/4-in.		1	1,024	--	--	--	--	--	--	--	--	--	--
		Total	10,382		1481		445		1096		68		61
Pinpoints	5 yrs	174	174	131	131	31	31	80	80	37	37	17	17
1/16-in.		48	192	65	260	15	60	21	84	9	36	8	32
1/8-in		16	256	11	176	8	128	13	208	--	--	--	--
1/4-in.		28	1,792	5	320	1	64	21	1344	1	64	--	--
1/2-in.		12	3,072	1	256	--	--	5	1280	--	--	--	--
		Total	5,486		1143		283		2996		137		49

Kind of Exposure	Age	Total Area of Rusting per Specimen		
		Cement 376	Cement 339	Cement 338
Laboratory	90 days	332.4	232.6	104.8
Laboratory	365 days	453	155.4	86.2
Sea Water	2 yrs	172.7	78.8	17.5
Sea Water	4 yrs	1913	258	84
Sea Water	5 yrs	2827	427	111

Note: Pinpoints were regarded as having unit area; 1/16-in. spots, an area of 4; 1/8-in. spots, 16; 1/4-in. spots, 64; 1/2-in. spots, 256; 3/4-in. spots, 1024.

Table 5

Results of Mortar Bar Expansion Tests for Sulfate Resistance of Two High-C_3A Cements

Age days	Expansion, % × 10^3: Mortar Bars with Added Sulfate, Test 1, Cement 332	Test 1, Cement 334	Test 2, Cement 332	Test 2, Cement 334	Lean Mortar Bars, Cement 332	Lean Mortar Bars, Cement 334
7	51	54	40	51		
14	79	89	65	83	8	13
21	102	117	84	107	16	30
28	124	142	105	130	27	51
35	--	--	--	--	117	93
42	--	--	--	--	532 (719, 346)	160
49	--	--	--	--	--	262
56	324	246	240	210	--	429
63	--	--	--	--	--	750
70	--	--	--	--	--	1235 (1314, 1081, 1310)
		--	--	--	--	--
84	346	354	268	295	--	--
112	347	480	268	410	--	--
140	348	724	269	585	--	--
168	347	1472	269	1105	--	--
196	348	1762	269	1312	--	--
224	353	1768	270	1326	--	--
252	352	1768	269	1326	--	--
280	351	1768	270	1328	--	--
308	351	1768	270	1328	--	--
336	353	1770	272	1331	--	--
364	354 (392, 325, 333, 349, 355, 369)*	1772 (1759, 1786)	272 (272, 261, 273, 280, 272, 275)	1332 (1341, 1257, 1282, 1364, 1355, 1395)	--	--

* Values in parentheses are expansions measured on individual bars at end of test.

Table 6

Results of Mortar Bar Expansion Tests for Sulfate Resistance of Two High-C_3A Cements with and Without Slag

Age Days	Expansion, % × 10^3 and Percent of No Slag Value											
	Lean Mortar Bars						Added-Sulfate Mortar Bars					
	Cement 332			Cement 334			Cement 332			Cement 334		
	No Slag	Slag 296	Slag 216(4)	No Slag	Slag 296	Slag 216(4)	No Slag	Slag 296	Slag 216(4)	No Slag	Slag 296	Slag 216(4)
28	27	20(74)*	24(89)	51	19(37)	22(43)	105	117(111)	133(127)	130	115(88)	126(97)
42	532	27(5)	32(6)	160	24(15)	28(17)	--	--	--	--	--	--
56	--	30	36	429	27(6)	31(7)	240	205(85)	153(64)	210	169(80)	191(91)
70	--	36	42	1235	31(3)	36(3)	--	--	--	--	--	--
84	--	40	45	--	34	38	268	222(83)	155(58)	295	228(77)	228(77)
154	--	109(20)	79(15)	--	44	48	--	--	--	--	--	--
196	--	--	104(20)	--	48	52	269	222(83)	158(59)	1312	331(25)	246(19)
364	--	--	--	--	70(6)	68(6)	272	224(82)	157(58)	1332	333(25)	250(19)

* Values in parentheses denote percentage of the expansion measured on the mortar bars without slag.

Table 7

Results of Added-Sulfate Mortar Bar Tests on Portland and Portland Blast-Furnace Slag Cements

Cement	Type	SO_3 %	Constituents of Batch for Bars: Cement g	Molding Plaster g	Water ml	Sand g	Expansion, % × 10^3, at Days Age: 7	28	84	140	196	252	308	364	Range of Values at 364 Days Age
330	II	2.00	361.2	38.8	216	1100	36	65	100	115	128	132	134	136	134 to 141
337	IS	2.22	362.8	37.2	216	1100	51	100	150	155	158	158	160	162	153 to 169
338	IS	2.39	364.0	36.0	216	1100	97	159	163	164	168	168	169	172	166 to 177
339	IS	2.12	362.0	38.0	216	1100	57	154	426	428	432	432	433	436	411 to 474
340	IS	2.69	366.0	34.0	216	1100	56	144	451	687	689	688	688	690	654 to 752
341	IS	1.28	356.4	43.6	216	1100	49	104	188	282	392	390	390	392	153 to 762
345	IS	2.37	363.2	36.4	216	1100	45	100	252	292	294	292	292	295	284 to 310
342	IS-A	2.59	365.2	34.8	216	1100	49	105	202	200	201	200	200	203	192 to 211
336	IS(E)	2.52	364.8	35.2	216	1100	36	55	70	74	82	83	85	89	81 to 93
339-D (80-20)	IS + N	2.07	361.6	38.4	224	1100	62	104	206	237	240	241	243	245	237 to 252
339-E (75-25)	IS + N	2.07	361.6	38.4	224	1100	65	102	182	208	211	212	214	216	207 to 225
339-F (70-30)	IS + N	2.06	361.6	38.4	224	1100	68	103	168	192	195	196	199	200	192 to 211
341 (Rerun)	IS	1.31	356.4	43.6	216	1100	50	104	250	466	602	618	--	--	--
341 Original Round 1	--	--	--	--	--	--	52	109	246	480	750	749	746	748	735 to 762
341 Original Round 2	--	--	--	--	--	--	46	100	150	150	152	152	153	155	153 to 158

Table 8

Portland Blast-Furnace Slag Cement Program, Examination of Added-Sulfate Test Mortar Bars

Cement	SO_3 in Cement %	Expansion at 1 yr %	Condition
341 Batch 1	1.28	0.748	Surfaces highly iron stained, especially where they rested on supports; surfaces pockmarked (lean mortar); abundant surface cracking in network; abundant sulfoaluminate in voids, some at aggregate-paste interfaces; sulfoaluminate in largest crystals and most completely filling voids near surfaces; some $Ca(OH)_2$ plates in a few voids, mortar very white and powdery. Bar easily broken in hand (bar No. 1)
340	2.69	0.690	Surfaces as described above; abundant small microcracks on surface; abundant sulfoaluminate in interior voids; voids nearest surfaces are nearly filled with, and contain the largest crystals of sulfoaluminate while innermost voids are not so full and contain very small spherulites of sulfoaluminate. Bar easily broken in hand (bar No. 6)
339	2.12	0.436	Surfaces as above but only a few scattered microcracks on surfaces of bars; bars of batch 1 have considerably more cracks than batch 2; sulfoaluminate in most voids occurring as described above. Some of the looser aggregate grains are lined with small puffy spherulites of sulfoaluminate. Bar very strong; could not break in hand (bar No. 6)
345	2.37	0.295	Surfaces as above but no cracking. Sulfoaluminate present as long needles nearly filling some voids nearest surface and in small, puffy spherulities in inner voids. Bars seem to have more voids than usual. Bar easily broken in hand (bar No. 6)
342	2.59	0.203	As above
338	2.12	0.172	Surfaces as above but no cracking. Sulfoaluminate in small, puffy aggregations (spherulites) partially lining most cavities. Bar very strong; could not break in hand (bar No. 6)
337	2.22	0.162	Surfaces as above but no cracking; sulfoaluminate present as above; freshly broken interiors are mottled dark greenish-gray. Bar very strong (bar No. 5)
341 Batch 2	1.28	0.155	Surfaces stained and pockmarked as above; sulfoaluminate present as long needles nearly filling outer voids and as small spherulites in inner voids; some voids partially filled with $Ca(OH)_2$ plates and sulfoaluminate while others are empty. Bar very strong (bar No. 4)
336	2.52	0.089	Surfaces as above; few $Ca(OH)_2$ plates in some voids; no sulfoaluminate. Bar very strong (bar No. 6)
330	2.0	0.136	Surfaces are highly iron stained, especially where bars rested on supports; surfaces are heavily pockmarked. Interior voids are sometimes filled or partially filled with clear $Ca(OH)_2$ plates, some having hexagonal outlines. No sulfoaluminate or cracking is present. Bars are very hard to break in hand. Breaks through and around aggregate (bar No. 1)
339-D (20% natural)	2.07	0.245	Surfaces are light buff-gray, no iron staining; surfaces are heavily pockmarked (lean mortar); sulfoaluminate present as small, puffy aggregations (spherulites) partially lining all voids. No cracking. Bars are very strong (bar No. 6)
339-E (25% natural)	2.07	0.216	As above; sulfoaluminate present in approximately the same abundance and form as in 339-D. Bars very strong (bar No. 1)
339-F (30% natural)	2.06	0.200	As above; surfaces are spotted with green algae (bar No. 6)

Table 9

A/F Ratios of Clinkers Used in Portland Blast-Furnace Slag Cements Program

Cement	Al_2O_3, %	Fe_2O_3, %	A/F Ratio
340	7.06	2.88	2.45
339	5.69	3.77	1.51
341	6.04	2.11	2.86
345	6.45	2.85	2.26
342	6.25	3.56	1.76
338	6.43	3.24	1.98
337	6.01	3.17	1.90
336	2.87	3.20	0.90

Note: Swayze[12] says that in clinkers with A/F ratios above 1.6, cooled slowly enough to prevent the formation of glass, the iron phase will be C_6A_2F. Cements 339 and 336 do not meet this requirement; the others do. None have A/F ratios below 0.84, so none fall in the region where the iron phase should be $C_6A_xF_y$. Cements 339 and 336 fall in the range where the composition of the iron phase is varying and is regarded as incalculable.

Table 10

Locations of Aluminoferrite, Aluminate, and C_3S Peaks from Diffraction Charts of Portland Blast-Furnace Slag Cement Clinkers

Cement	Alumino-ferrite d in angstroms	Aluminate d in angstroms	C_3S d in angstroms
340	2.650	2.696	2.974
339	2.646*	2.700	2.976
341	2.652	2.694	2.973
345	2.651	2.698	2.974
342	(2.649)	(2.702)	(2.982)
338	2.653	2.698	2.972
337	2.653	2.696	2.976
Mean	2.6518**	2.6970†,††	2.9740†,††
Standard deviation(e)‡	0.00132	0.00210	0.00161
Standard error‡‡	0.00059	0.00086	0.00066
Number of observations	5	6	6
Observed range	0.003	0.006	0.004

* Composition in range supposed to give solid solution of incalculable proportions. Composition of others C_6A_2F, according to Swayze.[12]

** Omitting 339, for reason given in above footnote, and 342 because the specimen surface was not plane.

† Calculated omitting 342, since the value it gave for the C_3S peak and for two other mixed silicate peaks differed so much from the others that it was concluded that the specimen did not have a plane surface.

†† NBS Circular 539 shows d = 2.700 Å for tricalcium aluminate.

‡ Calculated in the small sample form.

‡‡ Standard error of mean = $\frac{\text{Standard deviation}}{\sqrt{n}}$

Table 11

Relation of Expansion Results to Information on C_3A Content of Cements

Cement	Expansion at 364 days per Unit of Clinker %	Expansion at 365 days %		Clinker in Cements %	Calculated C_3A*		Counts/sec on 2.70 Å Peak	Ranking from Curves			
								C_3A		C_3S	
		Lean Mortar	Added Sulfate		Standard	Swayze		Amount	Xlinity	Amount	Xlinity
339	0.0073	0.386	0.436	60	8.7(5)	8.7(2)	130(3,4)	3	1	2	1
345	0.0051	0.292	0.295	58	12.3(1)	7.4(3)	130(3,4)	2	4	4	3
342	0.0038	0.075	0.203	60	10.5(4)	4.5(5)	200(1)	1	5	3	4
338	0.0031	0.056	0.172	55	11.6(2)	10.9(1)	150(2)	4	2	5	5
337	0.0028	0.072	0.162	57	10.6(3)	5.2(4)	125(5)	5	3	1	2
340	0.01015	--	0.690	68	13.8(1)	12.1(1)	215(1)	2	3	5	5
339	0.00727	--	0.436	60	8.7(5)	8.7(3)	130(4,5)	5	1	1	2
341	0.00997**	--	0.748†	75	12.4(2)	8.9(2)	190(3)	3	2	4	1
345	0.00509	--	0.295	58	12.3(3)	7.4(4)	130(4,5)	4	4	3	3
342	0.00383	--	0.203	60	10.5(4)	4.5(5)	200(2)	1	5	2	4

* Values in parentheses are expansions measured on individual bars at end of test.

** Computed as $\frac{0.748}{75}$.

† Average for two rounds of tests; round 1 showed 0.748; round 2, 0.155.

Table 12

Ranking of Cements Relative to Sulfate Resistance

Cement	Expansion at 365 days, %		Clinker in Cement	Expansion per Unit of Clinker	Ranking from Curves				% Clinker × Calculated Values		Counts × 10^{-2} × % Clinker
					C_3A		C_3S				
	Lean Mortar	Added-Sulfate Test	%	%*	Amount	Xlinity	Amount	Xlinity	Standard	Swayze	
341	0.420	0.748	75	0.0052	3	4	5	1**	9.3(2)	6.7(2)	14.2(2)
340	0.166	0.690	68	0.0101	2	5	6	7	9.4(1)	8.2(1)	14.6(1)
339	0.386	0.436	60	0.0073	5	1	2	2	5.2(7)	5.2(4)	7.8(5)
345	0.292	0.295	58	0.0051	4**	6	4	4	7.1(3)	4.3(5)	7.5(6)
342	0.075	0.203	60	0.0034	1	7	3	5	6.3(5)**	2.7(7)	12.0(3)
338	0.056	0.172	55	0.0031	6**	2	7	6	6.4(4)	6.0(3)	8.2(4)
337	0.072	0.162	57	0.0028	7**	3	1	3	6.0(6)	3.0(6)	7.1(7)**
336	0.024	0.089	38	0.0023	nd	nd	nd	nd	0.8(8)**	0.8(8)**	0.4(8)**

Round 1, 0.748

Round 2, 0.155

Note: nd means not determined.
* Based on added-sulfate test.
** Same rank as given by expansion results.

Table 13

Results of Testing for Dynamic Modulus of Elasticity of Concrete Beams
Containing Portland Blast-Furnace Slag Cements Exposed at
Treat Island, Maine, and St. Augustine, Fla., 1956-1963

Cement	Beam No.	0 Cycles 1956	146 Cycles 1957	[illegible] Cycles 1958	359 Cycles 1959	[illegible] Cycles 1960	[illegible] Cycles 1961	[illegible] Cycles 1962	[illegible] Cycles 1963	[illegible] Cycles 1964	Cement	Beam No.	E 1956	E 1958	E 1960	E 1962	E 1963
		Treat Island Beams										**St. Augustine Beams**					
330 Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	330	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
337 Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	337	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
338 Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	338	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
339 Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	339	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
340 Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	340	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] Type II	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

* [illegible]

Table 13 (Concluded)

Cement	Beam No.	0 Cycles 1956	144 Cycles 1957	[illegible] Cycles 1958	365 Cycles 1959	436 Cycles 1960	577 Cycles 1961	666 Cycles 1962	772 Cycles 1963	907 Cycles 1964
		% E								
		Trout Island Beams (Continued)								
336 Experimental	15T-2	100	109	117	115	*	—	—	—	—
	15T-4	100	111	117	116	114	109	112	112	110
	15T-6	100	111	119	116	115	110	122	116	117
	15T-8	100	117	123	125	121	117	118	118	114
	15T-10	100	126	121	122	122	135	115	112	111
	15T-12	100	116	125	126	125	118	116	116	113
	15T-14	100	108	115	119	117	112	111	114	112
	15T-16	100	108	115	118	117	109	110	110	107
	15T-18	100	109	117	119	118	112	113	114	111
339-270 80-20	10ST-164	100	116	124	128	127	120	120	119	118
	10ST-166	100	115	120	123	120	113	115	116	109
	10ST-168	100	107	113	115	111	104	107	103	101
	10ST-170	100	114	121	123	*	—	—	—	—
	10ST-172	100	113	121	122	172	112	111	111	107
	10ST-174	100	116	117	120	117	108	110	108	105
	10ST-176	100	112	119	122	119	111	113	111	109
	10ST-178	100	111	118	120	118	110	110	111	110
	10ST-180	100	111	117	119	117	108	109	107	102
339-270 75-25	11ST-182	100	109	115	115	112	104	108	102	97
	11ST-184	100	105	110	113	113	102	103	101	94
	11ST-186	100	108	114	116	114	102	105	103	95
	11ST-188	100	119	125	129	128	120	121	121	118
	11ST-190	100	111	118	120	*	—	—	—	—
	11ST-192	100	109	117	118	116	106	102	108	106
	11ST-194	100	110	118	117	116	104	106	103	95
	11ST-196	100	106	114	111	179	93	92	92	83
	11ST-198	100	105	113	115	112	101	103	101	95
339-270 70-30	12ST-200	100	106	110	112	110	100	105	100	95
	12ST-202	100	102	109	109	105	93	95	94	92
	12ST-204	100	99	103	103	104	88	89	89	84
	12ST-206	100	100	104	100	100	94	87	78	74
	12ST-208	100	102	106	104	104	90	92	88	79
	12ST-210	100	111	117	116	126	103	107	103	100
	12ST-212	100	113	120	126	121	109	110	110	107
	12ST-214	100	117	123	126	124	114	118	118	111
	12ST-216	100	120	126	128	*	—	—	—	—

Cement	Beam No.	1956	1958	1960	1962	1964
		% E				
		St. Augustine Beams (Continued)				
336	15A-1	100	113	118	116	118
	15A-3	100	112	119	118	120
	15A-5	100	115	127	119	121
	15A-7	100	116	128	116	123
	15A-9	100	116	130	119	121
	15A-11	100	118	131	120	122
	15A-13	100	107	118	107	109
	15A-15	100	107	117	108	110
	15A-17	100	107	118	109	110
339-270 80-20	10SA-163	100	123	131	117	122
	10SA-165	100	124	134	120	122
	10SA-167	100	128	138	126	135
	10SA-169	100	124	127	117	118
	10SA-171	100	122	130	123	124
	10SA-173	100	123	130	114	115
	10SA-175	100	124	135	118	119
	10SA-177	100	124	136	124	125
	10SA-179	100	126	137	125	127
339-270 75-25	11SA-181	100	125	133	120	123
	11SA-183	100	123	131	119	119
	11SA-185	100	124	130	118	119
	11SA-187	100	128	138	123	123
	11SA-189	100	129	138	122	124
	11SA-191	100	127	136	125	126
	11SA-193	100	123	131	122	124
	11SA-195	100	123	[illegible]	118	120
	11SA-197	100	126	137	122	124
339-270 70-30	12SA-199	100	121	129	117	124
	12SA-201	100	118	125	114	120
	12SA-203	100	121	127	111	111
	12SA-205	100	125	129	127	128
	12SA-207	100	124	131	119	119
	12SA-209	100	122	128	117	116
	12SA-211	100	122	129	118	119
	12SA-213	100	130	138	125	125
	12SA-215	100	131	140	127	128

* Removed for [illegible] study in 1959.

Table 14

Data on Air Content and Resistance to Freezing and Thawing

Specimen	No. Voids/ Inches of Traverse*		Air-Volume, %*		Freshly Mixed Concrete** AEA ml/bag	Air-Volume %	Temperature °F	Resistance to Freezing and Thawing: Laboratory DFE†	Treat Island Rel E††
136 RC-330 II	10.84 9.32 7.71	9.29	4.82 6.16 5.19	5.4	92	6.0	86	51	120
26 337 IS	8.44 8.85 5.39	7.56	3.70 4.51 3.84	4.0	58	5.5	82	45	125
40 338 IS	9.42 8.05 8.23	8.63	4.80 5.24 5.72	5.3	75	5.6	85	44	125
58 339 IS	12.42 11.44 12.78	12.22	5.92 5.39 5.63	5.7	75	6.2	87	53	125
80 340 IS	10.38 7.87 8.20	8.82	5.52 6.72 6.62	6.3	50	6.5	80	41	112
94 341 IS	8.33 7.69 7.83	7.95	6.06 5.51 6.52	6.0	50	5.8	88	52	124
156 345 IS	10.01 9.25 7.70	8.99	5.90 5.12 5.67	5.6	58	6.0	77	34	113
110 342 IS-A	8.12 8.03 8.00	8.05	5.61 5.23 5.44	5.4	50	6.1	84	52	122
2 335 Expansion	7.86 7.39 9.50	8.25‡	5.56 6.13 5.20	5.6‡	67	5.9	84	41	114
170 339-270 80-20	11.87 10.88 11.90	11.55	5.64 5.84 4.96	5.5	68	6.0	69	37	111
190 339-270 75-25	10.66 6.66 6.33	7.88	4.79 4.30 3.77	4.3	75	5.6	69	3[illegible]	104
216 339-270	9.61 9.17 10.89	9.89	6.47 6.17 5.75	6.1	81	6.3	72	35	98

* Data reported by PCA.
** Data for individual round from which the specimen studied at PCA was made.
† Table 7 of first report of the series, TR 6-445.
†† Average of results for 1963 from table 13.
‡ Measurements for air shown here represent average of three slabs cut from each specimen.

Table 15

Expansion of Mortar Bars with Pyrex Glass Aggregate

Cement	Na_2O Equivalent %	Length Change, %		
		168 days	364 days	728 days
330	0.68	+0.104	+0.123	+0.127
336	0.65	-0.005	+0.003	+0.006
337	0.25	-0.013	-0.003	+0.001
338	0.38	-0.014	-0.006	-0.005
339	0.21	-0.017	-0.007	-0.001
340	0.67	+0.016	+0.026	+0.032
341	0.58	-0.013	-0.005	+0.003
342	0.41	-0.016	-0.007	-0.004
345	0.75	+0.041	+0.053	+0.055
80-20	0.33	+0.010	+0.017	+0.010
75-25	0.36	+0.011	+0.021	+0.015
70-30	0.39	+0.014	+0.027	+0.020

Table 16

Results of Tests of Concrete Prisms for Drying, Shrinkage and Expansion on Immersion

Cement	Length Change, % × 10^3							Coefficient of Linear Thermal Expansion × 10^6	Dynamic Modulus of Elasticity psi × 10^{-6}			Average Weight Difference, Expansion Specimens - Shrinkage Specimens at 28 ± 2 months, lb
	Shrinkage			Expansion					Shrinkage Specimens	Expansion Specimens		
	180 days	364 days*	28 ± 2 months	180 days*	364 days*	28 ± 2 months	40 ± 2 months	364 days	28 ± 2 months	28 ± 2 months	40 ± 2 months	
330	49	49	58	6	9	1	2	4.25	5.6	6.9	7.0	0.15
337	48	50	63	3	4	-25	-24	4.19	4.9	6.9	7.1	0.12
338	52	54	65	-1	1	-32	-30	4.19	4.7	6.9	7.0	0.11
339	56	57	68	1	1	-17	-20	4.17	4.5	6.7	6.9	0.15
340	48	51	60	0	1	-35	-33	4.17	4.9	6.9	7.0	0.15
341	47	48	60	-2	0	-23	-22	4.20	4.8	7.0	7.0	0.14
345	43	44	56	4	7	-56	-54	4.26	5.2	7.0	7.5	0.16
342	51	52	64	-1	1	0	-1	4.05	4.9	6.8	6.9	0.17
336	44	46	56	2	5	2	4	4.25	4.7	7.1	7.1	0.14
80-20	51	57	63	4	3	-14	-11	4.27	4.7	6.7	7.0	0.17
75-25	52	58	66	3	2	7	9	4.40	4.7	6.6	7.0	0.15
70-30	52	59	66	8	4	-12	1	4.40	4.2	6.7	7.0	0.22

* Taken from table 7 of first report of this series.

APPENDIX A: OHIO RIVER DIVISION LABORATORIES INVESTIGATIONS

1. The Ohio River Division Laboratories has conducted four investigations of portland blast-furnace slag cements. One of these, covered by a report issued in October 1952, was an investigation of "portland-pozzolan cement"* that was proposed for use in the concrete for Lock No. 2 on the Monongahela River.[24**] The second, covered by a report issued in January 1957, was an investigation of blended cement concretes proposed for use on the Greenup Lock and Dam project.[25] The third, covered by a report issued in August 1960,[26] concerned the use of fly ash as a pozzolan in concrete made with portland blast-furnace slag cement. The fourth, covered by a report issued in April 1962,[27] concerned the effect of the addition of hydrated lime to mixtures containing both portland blast-furnace slag cement and fly ash. The following paragraphs summarize these reports.

Lock No. 2, Monongahela River[24]

2. The cements investigated were types IS-A and II-A manufactured by the same producer. The coarse aggregate was crushed limestone; the fine aggregate was natural sand. Proportions of the concrete mixtures used in tests to investigate the performances of the two cements were:

	Mixtures Used for	
	Strength Tests	Durability and Shrinkage Tests
Cement content, bags/cu yd	4.0	6.0
Water-cement ratio, by wt	0.51	0.49
Aggregate size, in.	3	1
Sand/aggregate, % by vol	28	40

3. Average results of tests performed on the freshly mixed and hardened concrete were:

	Cement	
	Type II-A Portland	Type IS-A Portland Blast-Furnace Slag
Slump, in.	3	2
Air content, %	6.6	4.5

(Continued)

* The "portland-pozzolan" cement studied was a portland blast-furnace slag cement and not a portland-pozzolan cement.

** Raised references refer to Literature Cited in main text.

	Cement	
	Type II-A Portland	Type IS-A Portland Blast-Furnace Slag
Compressive strength, psi		
7 days (6- by 12-in. cylinders)	2490	4200
28 days (6- by 12-in. cylinders)	4330	5360
(8- by 16-in. cylinders)	4290	4920
90 days (6- by 12-in. cylinders)	5280	6260
360 days (6- by 12-in. cylinders)	6405	6910
Flexural strength, 28 days, psi	580	745
DFE 300	75	49

4. Sulfate resistance was measured using mortar bars 2 by 2 by 11-3/4 in. in size containing the two cements and Ottawa sand, and using 3-in.-thick slices sawed from 6- by 12-in. cylinders of concrete containing the portland blast-furnace slag cement. The specimens were subjected to cycles of immersion in magnesium sulfate solution for 16 hr, and drying at 220 F for 8 hr. After 32 cycles the weight losses of the mortar bars were 1.3 percent for the portland cement, and 2.4 percent for the portland blast-furnace slag cement. The concrete discs made with portland blast-furnace slag cement showed no loss in weight after 26 cycles.

5. It was concluded that the portland blast-furnace slag cement was satisfactory for use in the concrete, and that it had advantages over the type II cement with which it was compared in having a lower heat of hydration, reduced bleeding, greater strength, and less shrinkage. As a result of these tests, type IS-A cement was successfully used on the Monongahela Lock No. 2 project.

Blended Cement Concretes for Greenup Lock and Dam[25]

Purpose of study

6. The study was conducted to determine the comparative properties of concrete made with the following types and blends of cements proposed for use in the construction of the locks at the Greenup Locks and Dam project:

a. Portland cement, type II

b. Portland blast-furnace slag cement, type IS

c. 50 percent type II cement and 50 percent type IS cement

d. 37-1/2 percent type II, 37-1/2 percent type IS, and 25 percent natural cement (type N)

e. 75 percent type IS cement and 25 percent natural cement (type N)

f. 75 percent type II cement and 25 percent natural cement (type N)

Concrete and mortar mixtures

7. Mortar mixtures. Mortar mixtures to determine the physical properties of the cements were made with each of the cements or blends. Concrete mixtures with cement contents of 3.5, 4.5, and 5.5 bags per cu yd were also made with each cement or blend of cements. A 3-in. maximum size coarse aggregate was used in the 3.5-bag mix, and a 1-1/2-in. maximum size in the balance of the concrete mixtures made for the strength determinations. Slumps of all mixtures were maintained within the range of 1 to 2-1/2 in. Air contents were held to the range of 5 $\pm$ 1 percent.

Test specimens

8. Two rounds were made of each mixture containing each of the six cements or blends. Eighteen 6- by 12-in. cylinders and six 6- by 20-in. beams were made from each round for strength tests. Three 4- by 5- by 16-in. specimens for use in determining drying shrinkage were cast from mixtures representing each of the six cements or blends. Also nine 3-1/2- by 4-1/2- by 16-in. specimens for freezing-and-thawing tests were made utilizing each of the six cements or blends. In addition, nine 2- by 2- by 12-in. prisms for strength tests were cast from mortar mixes made with each of the six cements or blends.

Test results

9. Materials. Results of tests of the cements, cement blends, and aggregates are described below.

a. Cement. Chemical analyses and physical properties of the cements and the calculated analyses of the blended cements are given in table A1.

b. Aggregates. The sand consisted of: limestone, 50 percent; quartz, 20 percent; igneous and metamorphic rock particles, 16 percent; sandstone, 12 percent; chert, 2 percent (about 1/2 the chert was chalcedonic). About 6 percent of the sand particles were badly weathered. The coarse aggregate was medium- to fine-grained buff to gray dolomitic limestone of which about 2 percent was weathered. About 70 percent of the buff material was made up of the rock and had a few stylolites and locally developed argillaceous partings.

10. Concrete and mortar. A summary of data, including slump and air contents, of the various mixtures from which strength test specimens were cast is given in table A2. Data pertinent to the concrete used in fabricating freezing-and-thawing test specimens and to the bleeding tests are included in table A3. Mortar and hardened concrete strength data are summarized in tables A4 and A5. Detailed values for each mixture are given in the tables. Strength and strength gain characteristics of the cements and blends are shown graphically in figs. A1-A8.

11. The percentages of shrinkage shown by the specimens from the several mixtures when drying from a saturated, surface-dry condition to a constant, oven-dry weight are given in the following tabulation:

Cement or Blend	% Drying Shrinkage of Mixtures with Cement Factors of 3.5	4.5	5.5
Type II	0.033	0.033	0.035
Type IS	0.032	0.029	0.034
50% type II 50% type IS	0.035	0.030	0.039
75% type IS 25% type N	0.031	0.032	0.039
75% type II 25% type N	--	0.035	0.039
37-1/2% type II 37-1/2% type IS 25% type N	0.032	0.031	0.036

12. Coefficients of linear thermal expansion were determined for concretes made with each cement or blend of cements. These coefficients were found to be as follows:

Cement or Blend	Coefficient of Expansion x $10^6/^oF$ for Cement Factors of 3.5	4.5	5.5
Type II	5.5	5.0	5.3
Type IS	5.3	5.6	5.6
50% type II 50% type IS	5.1	5.0	5.5

(Continued)

Cement or Blend	Coefficient of Expansion x $10^6/^{o}F$ for Cement Factors of 3.5	4.5	5.5
75% type IS 25% type N	5.1	5.1	5.6
75% type II 25% type N	4.9	4.8	4.8
37-1/2% type II 37-1/2% type IS 25% type N	5.3	5.1	5.1

Discussion of test results

13. Materials.

a. Cement. An examination of table A1 will show that the basic cements, type II, type N, and type IS, met the requirements of their respective specifications with the exception of the autoclave expansion of the type II cement. A check test made with the same brand of cement, but obtained from a different local source, showed an expansion well within specification limits, and it is believed that the excessive expansion measured in the original test was due to a faulty specimen or an error in procedure. The type II cement and the blend of 75 percent type II, 25 percent type N both show total alkali contents in excess of 0.6 percent.

b. Aggregates. The use of natural fine aggregate and crushed dolomitic limestone coarse aggregate had been approved for the Greenup project; however, at the time this investigation was started, the plants which would furnish the aggregates to the project were not in operation. In order to expedite the program, similar types of aggregates were obtained from two other sources in Ohio.

14. Mortars. During mixing of mortars made with the various cements, little difference was noted in the quantity of water required to produce the specified flow of 110 to 115 percent. The compressive and flexural strengths of the different mortars varied considerably as shown in figs. A1 and A2; however, the rates of strength gain were approximately the same for all the mortars. Table A4 includes a percentage comparison of the mortars using the type II cement mortar as a base.

15. Concrete. Results of tests of the plastic concrete, summarized in table A2, reveal no appreciable difference in the character of the

plastic concretes which could be attributed to an individual cement or blend. The results of freezing-and-thawing tests of the hardened concrete, conducted in accordance with Corps of Engineers Method CRD-C 114, are given in table A3. These test results show that all mixtures had good durability, but they give no indication of relative resistance to the test procedure of the different cements.

16. The strength summaries, figs. A1-A8 and table A5, show that varying but generally satisfactory strengths were developed by all of the mixtures. Compressive strengths shown by 10 of the 18 mixtures continued to increase through the 2-yr test period. Of the remaining 8 mixtures, 4 reached maximum strength after 12 months curing and 4 after 6 months. The specimens from these 8 mixtures showed some regression in strength at the end of the test period. Maximum flexural strengths were shown by 9 mixtures at an age of 6 months, and specimens from only 2 mixtures, both with 100 percent type II cement, continued to gain in strength until the end of the test period at 2 yr.

17. Tabulations given in paragraphs 11 and 12 show that the total drying shrinkage and the coefficient of linear thermal expansion of the concretes vary slightly with the cement or blend of cement used in the concrete.

Conclusions

18. Results obtained in this investigation indicate the following:

a. All cements and blends tested had satisfactory physical and chemical properties.

b. The total alkali content, expressed as soda, of the type II cement and the blend of type II and natural cement exceeded the limit specified for low-alkali cement.

c. The workability and water requirement of the plastic concrete mixtures were not greatly influenced by any of the cements or blends used.

d. Satisfactory durability was shown by the concretes made with all cements studied.

e. In general the cement blends studied will produce concretes equal or superior to that produced by type II cement alone.

f. The strengths obtained from concretes made with type IS cement are in general superior to similar concretes using type II cement.

g. Shrinkage and thermal expansion properties of the concretes studied were only slightly affected by the cements or blends studied.

Investigation of Fly Ash-Portland Blast-Furnace Slag Cement Concretes[26]

19. The mixtures containing fly ash had higher water-cementitious materials ratios than those without fly ash. However, the quantity of water per cubic yard was essentially the same in all 3.5-bag mixtures, whether or not fly ash was used. This was also true of the 4.5-bag mixtures. The apparent increase is due to the fact that for equal volume, blends of cement and fly ash weigh less than portland cements.

20. The variation in the quantity of air-entraining admixture required to produce a given percentage of entrained air in the concretes was large. The following tabulation shows the quantities of a single strength (approximately 10 percent solids) air-entraining admixture used in the mixtures.

Basic Cement Factor	Fly Ash %	Ounces AEA per 94 lb Cement		
		Type II	Type IS	Type IS(MH)
		3-in. Concrete Mixtures		
3.5	0	3.5	7.6	7.5
3.5	20	4.6	7.1	7.6
3.5	30	7.9	9.0	10.4
4.5	0	3.2	7.5	8.2
4.5	20	6.2	8.2	8.9
4.5	30	8.2	13.9	15.6
		3/4-in. Durability Test Mixtures		
5.75	0	1.4	7.0	7.3
5.75	20	5.1	8.3	9.5
6.00	30	11.4	15.6	16.3

21. All of the mixtures produced cohesive, workable concretes, and no excessive bleeding was noted.

22. The compressive strengths of specimens cast from 3.5-bag mixtures using type II and type IS(MH) cements without fly ash were essentially equal at 28 and 90 days age. At ages of 7 days and 1 yr, however, the type II concrete showed 22 and 7 percent, respectively, greater strengths. At equivalent ages, specimens made with type IS cement had substantially higher compressive strengths than specimens from either the type II or type IS(MH) mixtures.

23. At a cement factor of 4.5 bags per cu yd, specimens cast from concrete made with type IS showed 30 to 40 percent higher strengths than those made with type II. Except for an age of 7 days, strengths of specimens made with the type IS(MH) cement were moderately higher than the type II specimens.

24. The substitution of fly ash for 20 percent of the volume of cement in the 3.5-bag concrete caused, when compared to the type II concrete without fly ash, reductions in strength at 7 days for the type II, type IS, and type IS(MH) concretes of 17, 11, and 44 percent, respectively. At 28 days, the type II-fly ash concrete had strengths 16 percent less than that without fly ash, and the type IS(MH)-fly ash concrete, 24 percent. The type IS-fly ash concrete showed 14 percent greater strength than the type II concrete. At ages of 90 days and 1 yr, strengths of the type II mixtures with and without fly ash were about equal, the type IS-fly ash strengths about 10 percent greater, and the type IS(MH)-fly ash strengths about 20 percent less than the type II concrete without fly ash.

25. Among the 4.5-bag concretes, those containing the blend of type II cement and fly ash showed better strength characteristics than either of the other blends at all ages except 28 days, at which age the strength of the type IS blend was slightly higher. The strengths of the type IS blend at 28 days and later ages were approximately the same as those of the type II concrete without fly ash. Strengths of the type IS(MH) blend concretes were from 60 to 94 percent of the type II concrete without fly ash.

26. A 30 percent fly ash replacement in the type II, 3.5-bag concrete caused strength reductions of 26 percent at 7 days, 17 at 28 days, 0 at 90 days, and 4 percent at 1-yr ages. The blended type IS concrete specimens showed 67 percent of the strength of those with type II cement and no fly ash at 7 days, and from 82 to 87 percent at later ages. The type IS(MH) blend showed only 47 percent of the strength of the type II cement concrete without fly ash at 7 days, and approximately 70 percent at later ages.

27. With a cement factor of 4.5, the blended type II cement concrete showed 21 percent less strength than the similar concrete without fly ash at 7 days age and 10 percent at 28 days. At 90 days and 1 yr, the

strengths of the two concretes were about equal. Blended type IS cement concretes showed 26 percent less strength at 7 days than the type II concretes without fly ash; at 28 days the more rapid early strength gain characteristics of the type IS cement were apparent, and the strength of the blended type IS concrete was about equal to that of the concrete with type II cement and no fly ash; however, at 90 days the strength of the type II concrete exceeded that of the blend by 13 percent. At 1 yr the strengths were equal. The blended type IS(MH) concrete showed 50, 26, 20, and 17 percent less strength than the concrete with type II cement and no fly ash at ages of 7, 28, and 90 days and 1 yr, respectively.

28. With the type II cement, the fly ash replacements produced lower strengths at early ages, but the strengths at 90 days and 1 yr were equal to the strengths of the mixtures without fly ash. This indicates normal pozzolanic action for the fly ash when used with type II cement. Concretes made with the type IS and type IS(MH) cements showed normal strength gain characteristics for the 3.5- and 4.5-bag mixtures. However, when fly ash replacements were used with these cements, lower strengths were obtained at all ages, and the strength gain curves remained essentially parallel to the curves for the basic mixtures. This indicates that the normal pozzolanic action did not occur when fly ash was used with the portland blast-furnace slag cements.

29. The following tabulation shows the percentage strength gains of the various concrete mixtures with fly ash in comparison with the corresponding basic mixtures without fly ash.

Cement bags/cu yd	Type	Fly Ash %	Strength, % 7-day	28-day	90-day	1-yr
3.5	II	0	100	100	100	100
		20	83	84	104	97
		30	74	83	100	96
3.5	IS	0	100	100	100	100
		20	72	82	86	88
		30	54	59	68	65
3.5	IS(MH)	0	100	100	100	100
		20	72	73	80	87
		30	61	67	76	76

(Continued)

an air-dry condition. All of the specimens tested in an air-dry condition showed higher compressive strengths than similar cylinders which had been initially moist-cured, then air-cured, and finally immersed in water; however, their strengths were still approximately 5 percent lower than the specimens which were moist-cured for the full period. A limited number of moisture determinations were made on the cylinders after they were tested. These tests indicated that the one-week soaking period restored moisture content of the air-cured specimens to within about 1 percent of that of the continuously moist-cured specimens.

33. The results of standard freezing-and-thawing durability tests, Method CRD-C 20-55, showed that any of the cements or cement-fly ash blends tested will produce concrete of good durability. A comparison of the durability test results of specimens subjected to the different types of preliminary curing showed that an intermediate period of air-curing improved the resistance of concrete to freezing-and-thawing. The improvement is more apparent as the percentage of fly ash replacement increases.

Conclusions

34. On the basis of tests conducted and results obtained, the following are concluded:

a. The type of cement, II, IS, or IS(MH), had little or no effect upon the characteristics of freshly mixed concrete.

b. The addition of fly ash as a cement replacement by equal volumes, within the limits investigated, did not affect the quantity of water required in a cubic yard of concrete to produce a given workability.

c. The quantity of air-entraining admixtures required in a mixture to produce a given percentage of entrained air was greater in concrete made with types IS or IS(MH) cement than for mixtures using type II cement. The partial replacement of cement by fly ash increased the requirement for air-entraining admixture in all of the mixtures.

d. Type II and type IS(MH) cements produced approximately the same compressive strengths in lean, 3.5-bag concretes at ages of 28 days or more. In concretes having a higher cement content, 4.5 bags, slightly higher strengths were developed by the type IS(MH) cement. At earlier ages a slight strength advantage was shown by the type II cement for both cement factors. Greater strength was produced by the type IS cement at all ages than either the type II or type IS(MH) cement.

e. The replacement of type II cement by fly ash in the

percentages covered by this study caused a reduction in the compressive strength of the concrete at 7-day and 28-day ages; however, at 90 days or later the mixtures containing fly ash were approximately equal or superior in strength to those made with no fly ash.

f. The substitution of fly ash for 20 to 30 percent of the volume of either type IS or type IS(MH) cement in concrete mixtures will produce a reduction in compressive strength of from 30 to 45 percent at 7 days, 20 to 30 percent at 28 days, and from 15 to 35 percent at later ages. These strength reductions are in the same order as the percentages of cement replaced with fly ash, which indicates that the fly ash is not effectively utilized as a cementing material.

g. The rate of strength gain for concretes containing fly ash, as well as those without fly ash, is accelerated by the continuous availability of excess moisture during the curing period.

h. Concretes of comparable, satisfactory durability can be made with types II, IS or IS(MH) cements, and with blends of these cements and up to 30 percent by volume of fly ash.

i. The use of fly ash as a partial replacement for cement is effective in the reduction of heat generated in a concrete by cement hydration.

Investigation of Effect of Added Hydrated Lime on Cement-Fly Ash Concrete and Mortar[27]

Background

35. Numerous studies have been made which show that the use of fly ash as a partial replacement (20 to 30 percent) for portland cement will reduce the early strength of the concrete, but that after about 90 days the strength generally will be equal to or higher than that obtained with comparable concrete without fly ash. However, few data are available on the strength gain of concrete made with portland blast-furnace slag cement and fly ash.

36. In a recently completed study[26] in which portland blast-furnace slag cements were used with 20 and 30 percent fly ash replacements, the concrete mixtures failed to show the typical strength gain characteristics. The strengths of the fly ash mixtures, up to an age of 1 yr, were comparable with those of mixtures having the same amount of portland blast-furnace

slag cement but without fly ash, thus indicating that the fly ash was not serving as a cementing material, but only as an inert filler. Since both the slag in the portland blast-furnace slag cement and the fly ash are materials requiring lime for chemical reaction, it was believed that the failure to develop normal strength gain might have been due to a deficiency in the amount of lime available in the concrete. In this case, the addition of a small amount of hydrated lime to the concrete should produce the pozzolanic action necessary for utilizing the fly ash as a cementing material.

Purpose and scope

37. This study was made for the purpose of determining whether or not strength-gain and ultimate strength characteristics of concrete and mortars made with blends of fly ash and portland blast-furnace slag cements can be improved by the addition of small amounts of hydrated lime to the concrete.

38. The report presented the data obtained in the mixing and testing of mortars and concretes made with type II and type IS(MH) cements, blends of these cements with fly ash, and with additions of various percentages of hydrated lime to the cement-fly ash blends. Tests were scheduled for 3, 7, and 28 days, 6 months, 1 yr, and 5 yr. The report presented data through 1-yr tests.

Materials

39. The following materials were used in the study.

a. Cements. A type II portland cement and a type IS(MH) portland blast-furnace slag cement.

b. Fly ash. Fly ash complying with Corps of Engineers Method CRD-C 262.

c. Lime. Hydrated lime complying with ASTM Designation: C 6 as modified by paragraph 15b(2) of Corps of Engineers Method CRD-C 263.

d. Aggregates. The fine aggregate was natural sand; the coarse aggregate was crushed dolomitic limestone.

Concrete mixtures

40. A mixture containing 4.5 bags of portland blast-furnace slag cement per cu yd and 1-1/2-in. maximum size aggregate was selected as the basic concrete mixture. The following five variations were made:

a. One hundred percent type IS(MH) cement.

b. Seventy-five percent type IS(MH) cement, 25 percent fly ash (by volume).

c. Seventy-five percent type IS(MH) cement, 25 percent fly ash (by volume); lime added in the amount of 2 percent of the volume of the cement.

d. Seventy-five percent type IS(MH) cement, 25 percent fly ash (by volume); lime added in the amount of 5 percent of the volume of the cement.

e. Seventy-five percent type IS(MH) cement, 25 percent fly ash (by volume); lime added in the amount of 10 percent of the volume of the cement.

41. Slumps of the mixtures were held within the range of 2 to 3 in. by varying the amount of mixing water used. Air contents of the concrete varied between 4.5 and 5.6 percent. Concrete mixtures similar to each of those listed above were used to make durability test specimens. In these mixtures, the maximum size aggregate was restricted to 3/4 in., and entrained air content to a range of 5.5 to 6.5 percent. No concrete tests were made using type II cement.

Mortar mixtures

42. Type II and type IS(MH) cements were both used in mortar mixtures. The mortar consisted of one volume of cement or cement-fly ash blend to 3.58 volume of sand. The flow was maintained within the range of 95 to 105 percent, and the air content between 18 and 22 percent. Each of the two cements were used in mortar mixtures having the cement, fly ash, and lime variations listed in paragraph 40 above.

Test results

43. Concrete mixtures. All of the concrete mixtures were plastic and workable. The addition of fly ash permitted a water reduction of 0.22 gal per bag; however, the addition of lime raised the water requirement to the equivalent or slightly higher than that of the basic mixture. The addition of fly ash resulted in an increased demand for air-entraining admixture of 0.3 oz per bag of cementitious material. Lime had no apparent effect on air entrainment until 10 percent lime was added, when an additional 0.2 oz of admixture was required. A substantial reduction in bleeding was shown by all of the fly ash and fly ash-lime mixtures over the mixtures made with type IS(MH) cement only. Compressive strength

specimens from the plain type IS(MH) cement concrete showed satisfactory values at all ages through 1 yr. The percentage strength gain from the 28-day age to 90 days was low, only 6 percent; however, judging from later test results, it is probable that an increase of approximately 20 percent should have been obtained. The substitution of fly ash for 25 percent of the type IS(MH) cement, both with and without lime added, caused a reduction in the 7- and 28-day strengths of the concrete. The loss ranged from 20 to 36 percent at 7 days to 15 to 26 percent at 28 days. The mixtures containing lime sustained the greater losses. At 90-day ages, the mixtures containing fly ash or fly ash and lime compared more favorably with that without fly ash. However, as discussed in the previous paragraph, it is believed that the 90-day strength of the mixture without fly ash was abnormally low. If this is the case, the strengths of fly ash mixtures would continue to be about 5 to 15 percent below that of the mixture without fly ash.

44. Durability test results for specimens cured 90 days showed equal resistance for concrete specimens containing type IS(MH) cement, type IS(MH) cement with a 25 percent replacement of fly ash, and with cement, fly ash, and 2 percent lime. Slightly lower resistance was shown by the specimens containing 5 and 10 percent lime. The specimens cured for 1 yr showed about the same relative resistance but at a lower level. This drop in the level of resistance at later ages had been experienced in other instances and may be due to greater saturation of the concrete during the longer curing period.

45. Mortar mixtures. In mortar mixtures made with type II cement having a partial replacement of the portland cement by a pozzolan such as fly ash, lime released by the hydration of the cement is generally considered to be adequate for the reaction needs of the pozzolan. However, this series of tests was included in the study for comparison with a similar series using type IS(MH) cement, and also to determine if the addition of small quantities of lime would improve the early strength gain characteristics of the type II cement-fly ash mixture. The mortars were uniformly cohesive and workable. Flows were maintained within the range of 95 to 105 percent, and air contents within the range of 19.6 to 21.5 percent. The use of fly ash as a replacement for 25 percent of the volume

of the cement had a negligible effect on the water requirements of the mixtures. Additions of 2 and 5 percent hydrated lime had no apparent effect on the plastic properties of the mortar. The mixture with a 10 percent addition of lime required slightly more water to obtain the minimum flow of 95 percent.

46. All of the mortars using type II cement in which fly ash was used had lower 3- and 7-day compressive and flexural strengths than the basic mix without fly ash at similar ages. At 28 days, lower strengths still were shown for all of the mixtures with fly ash or fly ash-lime except the mixture with 10 percent lime, which had attained strengths slightly greater than the control mixture. At 90 days the flexural and compressive strengths of the mixtures made with cement-fly ash and cement-fly ash plus 2 and 5 percent lime added were from 2 to 10 percent lower than the control mixture. The strengths of the mortar containing 10 percent lime were about 12 percent greater than the similar mortar without fly ash or lime. At 6 months and 1-yr ages, all of the mortars with fly ash or fly ash and lime showed higher strengths than the control.

47. The mortars made with the portland blast-furnace slag cement were plastic and easily worked. Flows and air contents were well within the limits set for the study. The use of fly ash had little or no effect on the water requirements. An increase in water content of about 2.4 percent was necessary when 10 percent lime was added to maintain a flow in the 95-105 percent range.

48. The flexural and compressive strengths of the mortar mixtures made with fly ash or with fly ash and added lime were in all cases except one lower than those of the mortar using type IS(MH) cement only. The one exception occurred at 90 days in the flexural strength of the mortar which contained 10 percent added lime. In this case the flexural strength was about equal to that of the control. At 180 days the indicated strengths of the mixture with type IS(MH) alone were substantially lower than at 90 days, while the balance of the mixtures generally showed little change. As a consequence, the strengths of the fly ash and fly ash-lime mixtures equaled or exceeded those of the control. One-year tests showed that the mortar made with type IS(MH) cement with no fly ash or lime had resumed its strength gain and had strengths superior to those of the mixture containing

25 percent fly ash. The mixtures containing added lime generally showed strengths slightly greater than those containing type IS(MH) cement alone or with a 25 percent fly ash replacement of the cement.

Conclusions

49. On the basis of the data presented here, the following conclusions are drawn:

a. Concrete made with a blend of type IS(MH) cement and fly ash (75 and 25 percent respectively by volume) will not attain the equivalent compressive strength of a similar concrete made with type IS(MH) cement alone within a 1-yr period.

b. The addition of hydrated lime in quantities up to 10 percent of the volume of the cementitious material is not beneficial to the strength of concretes made with a blend of type IS(MH) cement and fly ash.

c. Concretes made with either 100 percent type IS(MH) cement or a blend of 75 percent type IS(MH) cement and 25 percent fly ash have equivalent and satisfactory resistance to freezing-and-thawing in the durability test. Long-time moist-curing results in lower resistance in the durability test.

d. The addition of 2, 5, or 10 percent hydrated lime to mortars made with 75/25 blends of type IS(MH) and type II cements and fly ash slightly increases both the compressive strengths and flexural strengths of the mortars at ages up to 90 days. No beneficial effect from the lime can be noted in the 6-month and 1-yr test results.

Discussion

50. An examination of these data at the WES led to the following comments.*

a. Figs. A9-A11 show the strength-age relations. The group of curves in fig. A9 are for mortars made with portland blast-furnace slag cement, those in fig. A10 are for mortars made with type II portland cement, and those in fig. A11 are for concrete made with portland blast-furnace slag cement. The mortar strengths show the characteristic slight advantage of cement without pozzolan at the earlier ages and the slight advantage of cement-pozzolan blends at later ages. One effect of the presence of fly ash was to reduce the mortar strengths at earlier ages with both cements from those obtained without fly ash. With type II cement, all of the

* Furnished as information to OCE (ENGCW-EC) and Director, CRDL, with Memorandum (WESCI) dated 25 May 1962.

mortars with fly ash were stronger than the mortars without fly ash after 90 days. In the case of type II mortars with fly ash, the one without lime had the lowest strength at the two earliest ages and intermediate strengths thereafter, while the mortar with most lime had the highest or nearly the highest strength at all ages. A somewhat similar relation, varying only in detail, was noted with the fly ash mortars made with portland blast-furnace slag cement.

b. From these observations it could be concluded that the addition of lime was beneficial to the strength gain of pastes in mortar when fly ash was used, regardless of which type of cement was employed, and that the maximum amount of lime used was not necessarily in all cases the maximum from which benefit could have been obtained. The data do, however, also suggest that the benefit of lime to the fly ash-containing mortars was no greater with portland blast-furnace slag cement than with type II portland.

c. In the data on concrete, a different indication is observed. The concrete with fly ash to which no lime was added is at all ages stronger than similar concretes to which lime was added. The concrete with 2 percent lime was weakest in all cases with the concretes containing 5 and 10 percent lime being intermediate. This apparent indication of a pessimum lime content at the 2 percent level does not appear to be explainable on the basis of water-cement ratio, since, as indicated in the report, the water-cementitious material ratio for this mixture was intermediate, the one with zero lime being lowest and the one with 10 percent lime being highest. The previous indication that the fly ash acted only as aggregate is confirmed for the test at 7 days age and for the test containing 2 and 10 percent lime at 28 days. However, for other ages and other lime contents the fly ash is indicated to contribute significantly to strength, especially for the mixture containing no lime, for the strengths at ages of 28 days and later are probably of the order of 90 percent of the actual trend of strengths of concrete without fly ash.

d. One interesting aspect of these data is the difference in indication of effect of fly ash with and without lime between the mortar tests and the concrete tests. This difference may be in part related to differences in the basis employed in adjusting mixture proportions among the several mixtures involved. It is believed that this is a more likely explanation than one which requires the presence of the coarse aggregate in the concrete to participate chemically in the activity that produces the observed strengths.

e. The conclusions given in the report state that concrete made with a blend of portland blast-furnace slag cement and fly ash will not attain equivalent compressive strength to similar concrete without fly ash at an age of 1 yr. The

concrete reported on did not attain equivalent strength, but the generalization that such attainment is essentially impossible appears to overlook the possibility that different methods of adjustment of mixture proportions from those which were employed in the work being reported might so affect the strength-gaining characteristics as to reverse the relations. The conclusions also state that the mortars were not benefited from lime additions at ages greater than 90 days. In the case of the 1-yr tests with mortars with portland blast-furnace slag cement, the strengths of the three mortars containing fly ash and lime were all materially higher than the strength of the mortar with fly ash without lime and the three with lime were all higher than that containing neither lime nor fly ash.

Table A1

Chemical and Physical Properties of Cements and Blends Proposed for Use on Greenup Locks and Dam Project

Test Properties	Type Cement or Blend						
	Natural	Type II	Type IS	50% Type II 50% Type IS	75% Type IS 25% Type N	75% Type II 25% Type N	37.5% Type II 37.5% Type IS 25% Type N
Chemical Analysis							
Silica (SiO_2)	19.97	20.71	24.93	22.82	23.69	20.52	22.11
Alumina (Al_2O_3)	8.17	6.13	11.50	8.82	10.67	6.64	8.65
Ferric oxide (Fe_2O_3)	1.77	3.93	2.90	3.41	2.62	3.39	3.00
Lime (CaO)	47.52	61.80	53.44	57.62	51.96	58.23	55.10
Magnesia (MgO)	13.09	4.31	3.93	4.12	6.22	6.50	6.36
Sulfates (SO_3)	2.68	1.54	2.46	1.80	2.52	1.83	2.17
Ignition loss	6.09	0.90	0.34	0.62	1.78	2.20	1.99
Insoluble residue	3.75	0.11	0.18	0.15	1.07	1.02	1.09
Tricalcium silicate (C_3S)	--	42.9	--	--	--	--	--
Dicalcium silicate (C_2S)	--	27.1	--	--	--	--	--
Tricalcium aluminate (C_3A)	--	9.6	--	--	--	--	--
Tetracalcium alumina ferrite (C_4AF)	--	12.0	--	--	--	--	--
Soda (Na_2O)	0.11	0.20	0.15	0.18	0.14	0.18	0.16
Potassa (K_2O)	0.94	0.65	0.16	0.40	0.36	0.72	0.54
Alkalies as soda	0.72	0.62	0.25	0.44	0.37	0.65	0.51
Physical Properties							
Surface area (Blaine)	10,520	3160	3965	3560	5605	5000	5300
Specific gravity	2.964	3.154	3.040	3.097	3.021	3.106	3.064
Autoclave expansion, %	0.06	1.09*	-0.01	0.08	0.09	0.32	0.18
Air entrainment, %	--	11.3	6.9	10.6	9.2	13.9	10.9
Normal consistency, %	--	24.5	31.0	28.0	28.5	26.0	27.5
Setting time (Gillmore), min							
Initial	--	210	215	185	195	195	180
Final	--	410	430	385	380	360	370
Bleeding							
Rate of bleeding, cm/sec ($\times 10^6$)		67	113	67	83	20	57
Unit subsidence, cm/cm		0.011	0.015	0.012	0.013	0.015	0.014
Potential segregation, DW		0.033	0.045	0.036	0.039	0.045	0.042
Base W/C (a) gal/bag		5.68	5.57	5.66	5.63	5.57	5.60
Base W/C (b) gal/bag		5.77	5.79	4.54	5.73	5.85	5.72
Heat of hydration, 25 C							
7 days, cal/g		42.0	61.7	58.6	55.0	51.8	51.6
28 days, cal/g		58.1	59.5**	69.2	59.4	62.9	68.2

Note; Chemical analysis computed for blends.
* Sample obtained from Maysville F.P.P. showed expansion of 0.19%.
** Discrepancy probably due to error in manipulation.

Table A2

Summary of Data for Plastic Concretes, Greenup Locks and Dam Project

Type of Cement	Cement bags/yd	Water Cement Ratio by Wt	Slump in.	Air %	Mixture Proportions by Weight				
					Cement	Sand	3/4-in. Aggregate	1-1/2-in. Aggregate	3-in. Aggregate
Type II	3.5	0.623	2-1/4	4.2	1	3.11	1.97	2.26	2.82
	4.5	0.510	1-1/2	5.0	1	2.42	2.63	2.64	--
	5.5	0.445	2-1/2	5.0	1	1.91	2.08	2.08	--
Type IS	3.5	0.587	1-3/4	5.4	1	3.13	1.97	2.26	2.82
	4.5	0.515	1	4.6	1	2.39	2.61	2.62	--
	5.5	0.445	1	4.5	1	1.90	2.07	2.08	--
50% type II	3.5	0.593	2	5.6	1	3.12	2.00	2.28	2.86
50% type IS	4.5	0.540	1-1/2	5.7	1	2.39	2.60	2.61	--
	5.5	0.460	1-1/2	4.2	1	1.89	2.06	2.06	--
75 % type IS	3.5	0.609	2	5.9	1	3.10	1.98	2.26	2.84
25% type N	4.5	0.540	1-1/4	5.2	1	2.38	2.60	2.60	--
	5.5	0.461	1	4.8	1	1.89	2.06	2.06	--
75% type II	3.5	0.609	1-3/4	5.5	1	3.10	1.98	2.26	2.85
25% type N	4.5	0.540	2	5.2	1	2.38	2.60	2.60	--
	5.5	0.461	2	5.0	1	1.89	2.06	2.06	--
37.5% type II	3.5	0.609	2	5.6	1	3.11	1.98	2.26	2.84
37.5% type IS	4.5	0.530	1-3/4	5.2	1	2.39	2.60	2.61	--
25% type N	5.5	0.453	1-1/2	4.8	1	1.89	2.06	2.07	--

Table A3

Summary of Freezing-and-Thawing Test Data, Greenup Locks and Dam Project

(Method CRD-C 114)

Cement	Concrete Mix Data: Cement bags/yd	Concrete Mix Data: Water Cement Ratio	Concrete Mix Data: Slump in.	Concrete Mix Data: Air %	Concrete Mix Data: Bleeding %*	Percent Initial Dynamic Modulus of Elasticity after Indicated No. of Cycles of Freezing and Thawing: 50	100	150	200	250	300	DFE After 300 Cycles of Freezing and Thawing
Type II	5.25	0.49	2-3/4	7.0	18.9	90	87	85	85	84	82	82
			2	6.5		88	87	86	83	81	79	79
			2-1/4	6.3		88	88	86	83	81	78	78
Type IS	5.50	0.49	2	5.9	17.5	90	85	82	80	79	73	73
			2	5.9		87	85	85	82	80	77	77
			1-3/4	6.2		88	87	85	83	81	78	78
50% type II 50% type IS	5.50	0.49	2-3/4	6.0	20.6	87	85	83	81	78	76	76
			2-3/4	6.8		85	84	82	80	78	76	76
			2-3/4	6.5		86	83	82	79	78	75	75
75% type IS 25% type N	5.50	0.49	2	6.1	9.2	88	86	84	82	79	77	77
			2-1/4	6.1		87	84	83	81	78	76	76
			2-1/4	6.0		87	85	83	80	79	76	76
75% type II 25% type N	5.25	0.49	2	6.3	5.8	89	86	84	81	78	73	73
			2-1/4	6.8		89	86	85	82	79	78	78
			2-3/4	7.0		89	86	83	80	77	76	76
37.5% type II 37.5% type IS 25% type N	5.50	0.49	2	6.0	6.3	87	86	85	80	77	74	74
			2	6.8		88	86	85	82	78	76	76
			2	6.5		89	86	85	80	79	76	76

* Method CDR-C 9

Table A4

Mortar Strength Data, Greenup Locks and Dam Project

Strength		100% Type II psi	100% Type II %	100% Type IS psi	100% Type IS %	50% Type II 50% Type IS psi	50% Type II 50% Type IS %	75% Type IS 25% Type N psi	75% Type IS 25% Type N %	75% Type II 25% Type N psi	75% Type II 25% Type N %	37.5% Type II 37.5% Type IS 25% Type N psi	37.5% Type II 37.5% Type IS 25% Type N %
Compressive (2-in. modified cubes)													
7 days		3010		3865		1625		2980		2800		2930	
		3095		3855		1665		2990		2555		2775	
		3000		3930		1655		2975		2580		2835	
	Avg	3035	100*	3885	128*	1650	54	2980	98	2645	87	2845	94
28 days		3875		5915		2190		4905		3900		4210	
		4240		5290		2405		4490		3850		4630	
		3950		5525		2645		4370		3710		4490	
	Avg	4020	100	5575	139	2410	60	4590	114	3820	95	4445	110
105 days		4600		7475		3310		[illegible]		4825		4935	
		4295		7475		2900		5240		4220		5050	
		4270		7185		3245		5765		4555		5105	
	Avg	4390	100	7380	168	3150	72	5580	127	4535	103	5030	115
Flexural (2- by 2- by 12-in. prisms)													
7 days		685		850		445		675		640		710	
		[illegible]		850		445		715		660		740	
	Avg	685	100	850	124	445	65	695	101	650	95	725	106
28 days		770		1105		660		950		680		980	
		720		980		690		990		820		930	
	Avg	745	100	1040	140	675	91	970	130	750	101	955	127
105 days		875		1210		690		1125		990		1075	
		855		1210		710		1070		1035		1080	
	Avg	865	100	1210	140	700	81	1100	127	1015	117	1080	125

Note: Water-cement ratio, by weight, of all mixes was 0.50 or 0.51; mix proportions by weight were 1:2.75.
* Percent of value for type II cement.

Table A5

Summary of Strengths of Concrete Mixtures with Cement Factors of 3.50, 4.50, and 5.50; Greenup Locks and Dam Project

Strength	100% Type II		100% Type IS		50% Type II 50% Type IS		75% Type IS 25% Nat		75% Type II 25% Nat		37.5% Type II 37.5% Type IS 25% Type N	
	psi	%	psi	%	psi	%	psi	%	psi	%	psi	%
Cement Factor 3.50												
Compressive												
7 days	2300	100	2015	88*	1935	84	1815	79	1940	84	1735	75
28 days	3055	100	3315	108	3145	103	3085	101	3350	110	3205	105
90 days	3520	100	3750	107	3865	110	3385	96	3930	112	4265	121
6 months	3970	100	3890	98	4000	101	4095	103	4100	103	4340	109
1 yr	4170	100	4240	101	4025	97	4360	105	4380	105	4560	109
2 yr	4225	100	3880	93	4405	106	4290	103	4470	107	4875	117
Flexural												
7 days	395	100	360	91	365	93	310	79	390	99	330	84
14 days	--	--	--	--	--	--	--	--	--	--	--	--
28 days	530	100	560	106	565	107	555	105	585	110	580	109
90 days	700	100	685	98	665	95	675	97	645	92	715	102
6 months	705	100	685	97	675	96	760	108	750	106	635	90
1 yr	675	100	730	108	760	113	635	94	710	105	690	102
2 yr	770	100	680	88	710	92	615	80	645	84	660	86
Dynamic modulus $E \times 10^{-6}$												
7 days	4.52	100	4.27	95	3.59	79	3.62	80	3.73	83	3.61	80
14 days	--	--	--	--	--	--	--	--	--	--	--	--
28 days	5.12	100	4.92	96	4.76	93	4.49	88	4.87	95	4.79	93
90 days	5.56	100	5.29	95	5.66	102	5.08	91	5.21	94	5.44	98
6 months	5.64	100	5.12	91	5.75	102	5.70	101	5.57	99	5.58	99
1 yr	5.84	100	5.64	96	5.63	96	5.36	92	5.50	94	5.75	98
2 yr	5.81	100	5.52	95	5.52	95	5.13	88	5.58	96	6.23	107
Cement Factor 4.50												
Compressive												
7 days	2380	100	2905	122*	1980	83	2370	100	2245	94	2700	113
28 days	3425	100	4540	133	3075	90	3695	108	3560	104	4175	122
90 days	4215	100	5065	120	3505	83	3975	94	4075	97	4830	114
6 months	4850	100	5630	116	3945	81	5225	108	4475	92	5390	111
1 yr	4645	100	5340	115	4130	89	4600	99	4500	97	5650	122
2 yr	4620	100	5460	[illegible]	4410	96	5080	110	4610	100	5475	119
Flexural												
7 days	505	100	575	114	390	77	320	63	445	88	445	88
14 days	550	100	635	115	535	97	500	91	510	93	550	100
28 days	555	100	710	128	570	103	590	106	600	108	690	124
90 days	750	100	800	107	690	92	745	99	770	103	740	99
6 months	770	100	905	117	725	94	770	100	710	92	850	110
1 yr	785	100	860	110	710	90	645	82	665	85	815	104
2 yr	790	100	845	107	745	94	725	92	710	90	810	103
Dynamic modulus $E \times 10^{-6}$												
7 days	4.77	100	4.60	96	4.19	88	3.85	81	4.16	87	4.31	90
14 days	4.78	100	4.95	104	4.57	96	4.32	90	4.32	90	4.64	97
28 days	5.24	100	5.38	103	4.71	90	4.95	95	4.89	93	5.15	98
90 days	5.14	100	5.62	109	4.62	90	4.48	87	5.28	103	5.30	103
6 months	5.63	100	6.18	110	5.43	96	5.46	97	5.66	101	5.88	104
1 yr	6.00	100	6.24	104	6.33	109	5.69	95	5.75	96	5.85	98
2 yr	6.08	100	[illegible]	105	5.68	92	5.92	97	6.12	101	6.01	99
Cement Factor 5.50												
Compressive												
7 days	3315	100	3735	113*	3490	105	3850	116	3145	95	3360	101
28 days	4165	100	5290	127	5215	125	5675	136	4620	111	5585	134
90 days	4815	100	5885	122	5725	119	5945	123	5075	105	5690	118
6 months	5705	100	6425	112	6375	112	7445	130	5695	100	6040	106
1 yr	5335	100	6270	118	6495	122	6475	121	5670	106	6835	128
2 yr	5480	100	6675	122	7085	129	7450	136	5935	108	6760	124
Flexural												
7 days	525	100	595	113	585	111	560	107	570	108	550	105
14 days	645	100	635	98	660	102	680	105	610	95	605	94
28 days	680	100	785	115	760	112	775	114	690	101	735	108
90 days	820	100	990	121	900	110	960	117	785	96	900	110
6 months	835	100	955	114	905	108	1005	120	830	99	920	110
1 yr	930	100	980	105	950	102	910	98	800	86	880	95
2 yr	845	100	970	115	920	109	925	110	810	96	900	106
Dynamic modulus $E \times 10^{-6}$												
7 days	4.54	100	4.97	110	4.87	107	4.60	101	4.52	99	4.71	104
14 days	5.06	100	5.31	105	5.22	103	4.84	95	4.47	88	4.84	95
28 days	5.31	100	5.36	101	5.45	103	5.44	102	5.26	99	5.23	98
90 days	5.55	100	5.81	105	5.77	104	5.96	109	5.45	98	5.90	106
6 months	5.90	100	6.32	107	6.29	107	6.30	107	5.52	94	6.10	103
1 yr	5.70	100	6.40	112	6.47	104	6.38	112	5.70	100	6.12	107
2 yr	6.12	100	6.48	106	6.32	103	6.41	105	5.96	97	6.00	98

* Percent of value for type II cement.

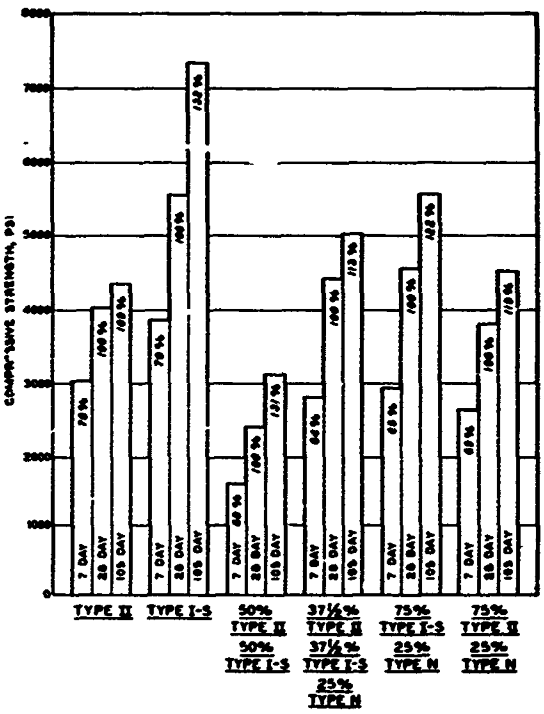


Fig. A1. Compressive strengths of mortars containing type II, type IS, and blends of these cements and type N cement

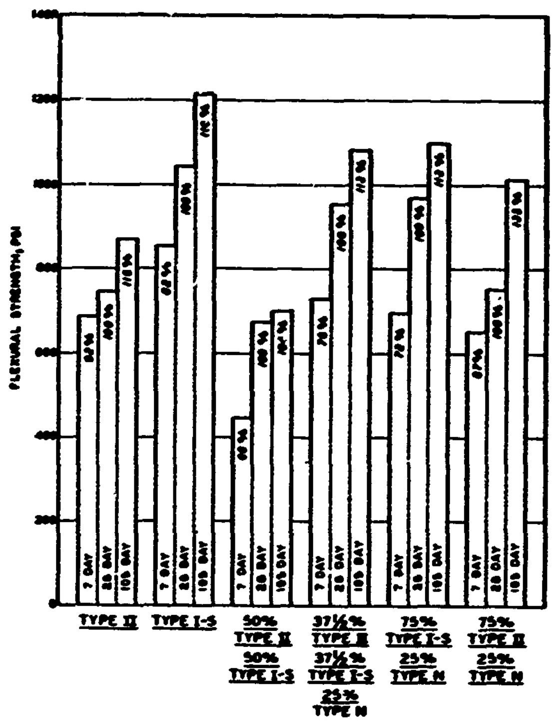


Fig. A2. Flexural strengths of mortars containing type II, type IS, and blends of these cements and type N cement

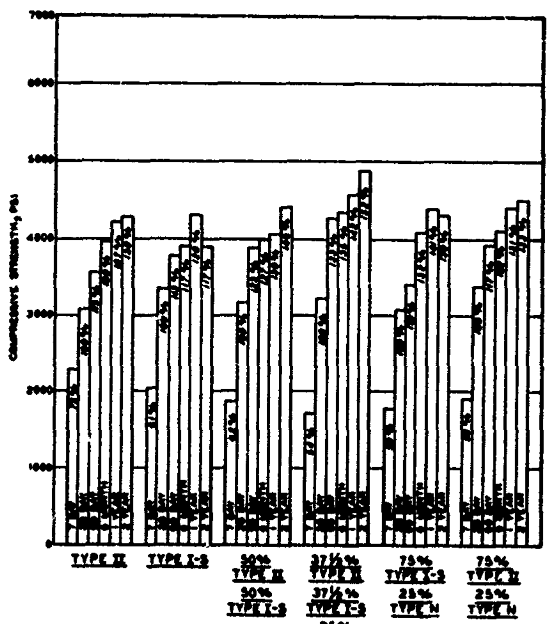


Fig. A3. Compressive strengths of concretes having a cement factor of 3.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

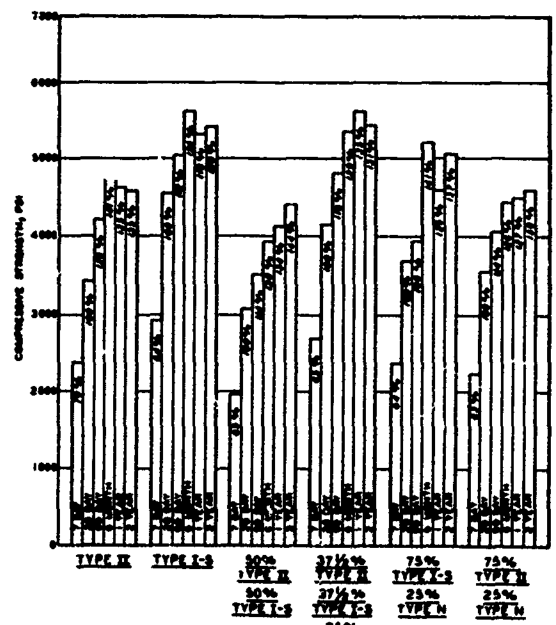


Fig. A4. Compressive strengths of concretes having a cement factor of 4.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

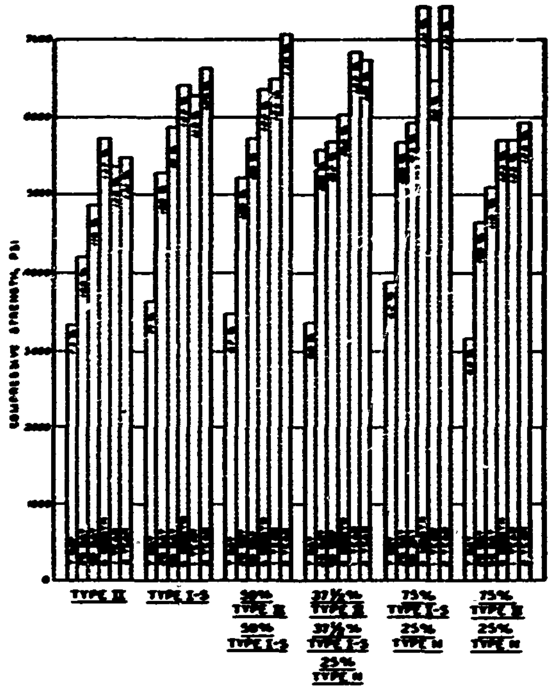


Fig. A5. Compressive strengths of concretes having a cement factor of 5.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

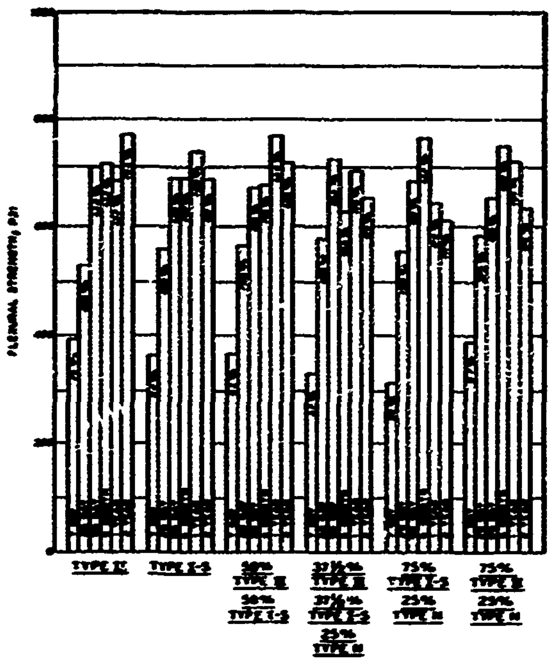


Fig. A6. Flexural strengths of concretes having a cement factor of 3.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

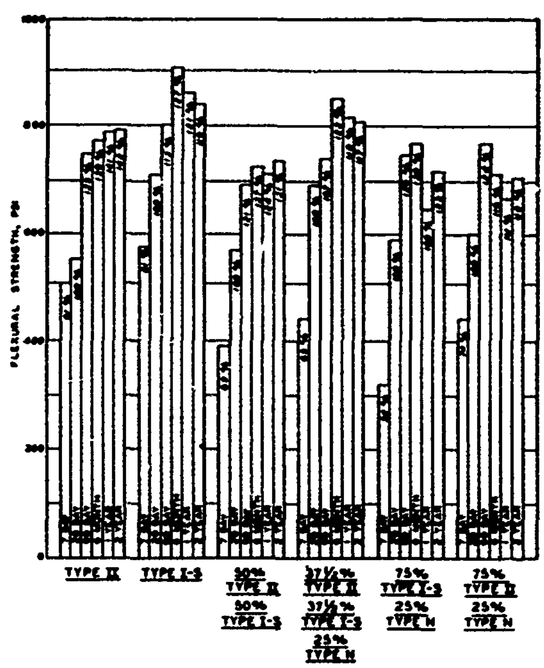


Fig. A7. Flexural strengths of concretes having a cement factor of 4.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

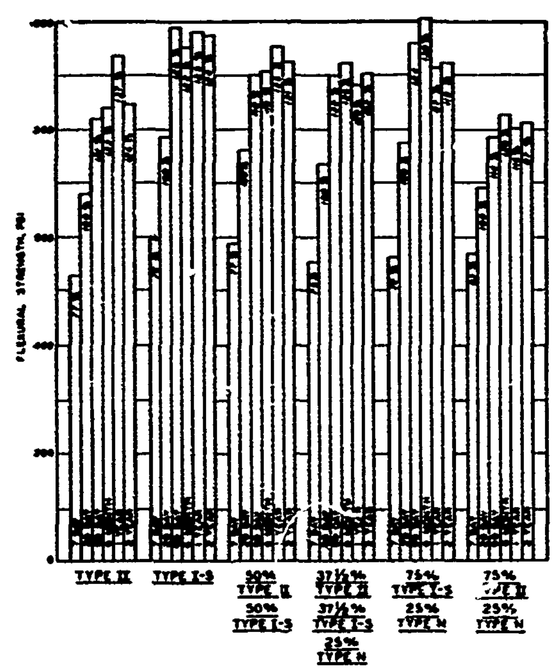


Fig. A8. Flexural strengths of concretes having a cement factor of 5.50 made with type II and type IS cements, a blend of these cements, and blends of these cements with type N cement

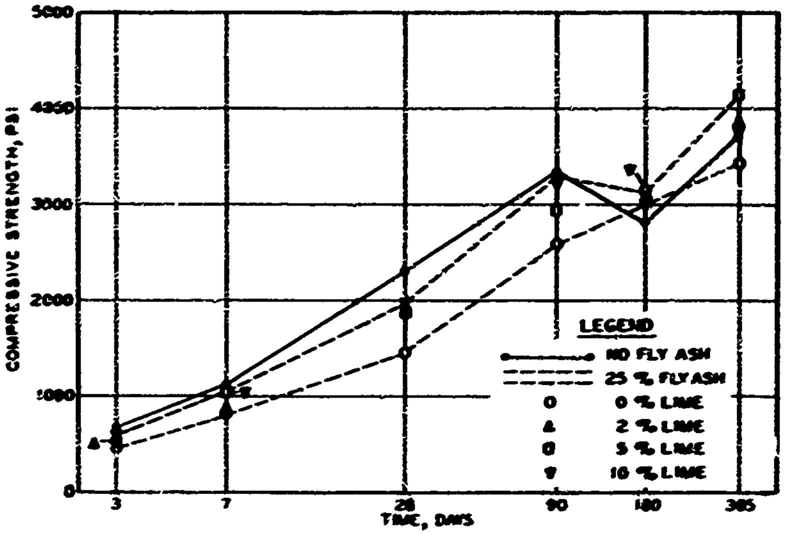
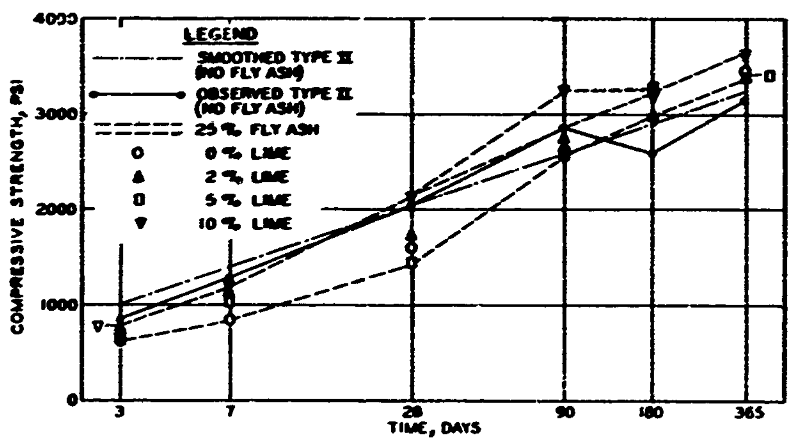


Fig. A9. Strength-age relation of mortars containing portland blast-furnace slag cement IS(MH), with and without fly ash and lime

Fig. A10. Strength-age relation of mortars containing type II portland cement, with and without fly ash and lime



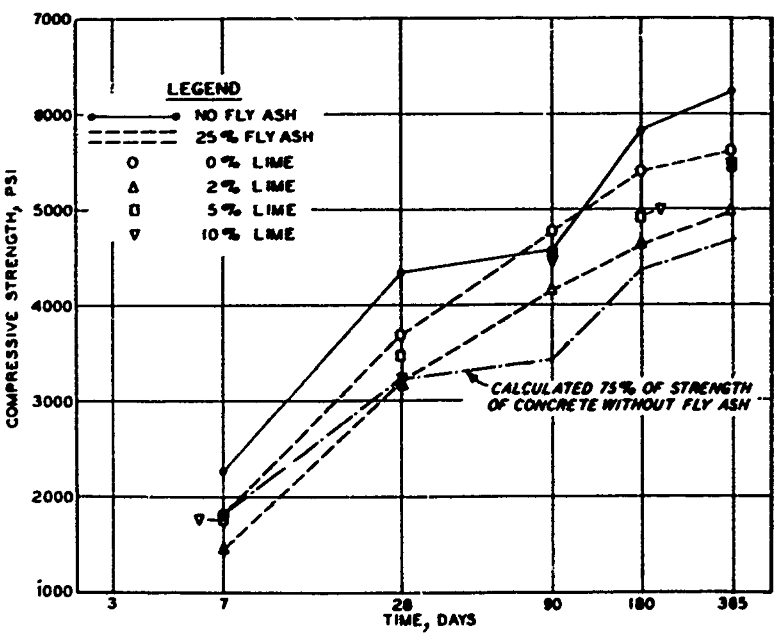


Fig. A11. Strength-age relation of concrete containing portland blast-furnace slag cement IS(MF), with and without fly ash and lime

APPENDIX B: MISSOURI RIVER DIVISION LABORATORY INVESTIGATION

Scope

1. A program was conducted to obtain comparative data on concretes made using types I and II portland and type IS portland blast-furnace slag cements. Concretes for strength tests were proportioned to have a cement content of 6.0 bags per cu yd, a slump of 1-1/2 to 2 in., and an air content of 4 to 7 percent. Compressive and flexural strength tests were made at ages of 7, 28, 90, and 365 days. Tests for resistance to freezing and thawing and for alkali-aggregate reaction expansion were made in accordance with standard procedures.

Materials

2. The materials used were:

Lab. No.	Material	Type or Size
55/96 A	Portland cement	I
55/96 B	Portland blast-furnace slag cement	I-S
--	Portland cement	II
55/96 C	Crushed gravel	No. 4 to 3/4-in.
55/96 E	Crushed gravel	3/4- to 1-1/2-in.
55/96 F	Natural sand	--
--	AEA	--

Cements

3. The portland blast-furnace slag cement had the following indicated composition by chemical analysis:

Determination	%	Determination	%
SiO_2	27.2	Sulfide sulfur	0.6
Al_2O_3	7.3	Insoluble residue	1.34
Fe_2O_3	2.2	Loss on ignition	0.8
CaO	54.4	K_2O	0.16
MgO	3.7	Na_2O	0.14
SO_3	2.3	Total alkali as Na_2O	0.25
Mn_2O_3	0.6	--	--

4. The results of other tests on the portland blast-furnace

slag cement and the type I portland were:

	Type I	Type IS
Normal consistency, % water	24.6	27.6
Specific gravity	--	3.00
Surface area, air permeability, sq cm/g	3430	4520
Retained on No. 325 sieve, %	--	2.2
Gillmore setting time, initial, hr:min	4:15	3:50
final, hr:min	6:15	6:05
Autoclave expansion, %	0.09	0.05
Compressive strength, psi, 3 days	1500	1420
7 days	2780	2370
28 days	4580	5320
Air content of mortar, %	7.6	5.1
Heat of hydration, cal/g, 7 days	--	62
28 days	--	77

Aggregate

5. The coarse aggregate used in these tests came from North Dakota. The fine aggregate came from Minnesota. Data on the aggregate are:

Coarse Aggregate

Sieve	Cumulative % Passing: No. 4 to 3/4 55/96 D	Cumulative % Passing: 3/4 to 1-1/2 55/96 E	Cumulative % Passing: 55% 55/96 D 45% 55/96 E
2-in.	--	100.0	100.0
1-1/2-in.	--	96.3	98.3
1-in.	100.0	44.8	75.1
3/4-in.	90.3	13.5	55.7
1/2-in.	53.6	4.1	31.3
3/8-in.	33.2	2.7	19.5
No. 4	8.0	1.7	5.2
Bulk specific gravity (saturated, surface dry)	2.69	2.71	--
Absorption, %	0.7	0.5	--

Fine Aggregate

Sieve	Cumulative % Passing
3/8-in.	100.0
No. 4	96.9
No. 8	82.4
No. 16	65.0
No. 30	41.2
No. 50	17.1
No. 100	5.1

(Continued)

Fine Aggregate

Sieve	Cumulative % Passing
No. 200	3.0
Fineness modulus	2.92
Bulk specific gravity (saturated, surface dry)	2.62
Absorption, %	2.0

Strength Tests

Concrete mixtures

6. Concrete mixtures for strength tests were proportioned by the trial batch method and were as follows:

	Cement		
	Type I	Type IS	Type II
Theoretical cement factor, bags/cu yd	6.29 to 6.30	6.34 to 6.35	6.34
Water-cement ratio, by wt	0.43	0.44	0.42
Sand, % of total aggregate, by volume	33	31	35
Actual cement factor, bags/cu yd	5.88 to 5.97	5.97 to 6.01	5.98
Air content, %	5.2 to 6.4	5.4 to 5.8	5.6
Slump, in.	1-1/2 to 2	2 to 2-1/2	2-1/4
AEA used, oz/bag	3.48 to 3.78	6.06 to 6.53	2.57

7. Mixtures with types I and IS cement were made on each of four consecutive days; one mixture was made with type II cement.

Concrete specimens

8. Three 6- by 6- by 30-in. beams and three 6- by 12-in. cylinders were molded from each batch made with types I and IS cement. Cylinders and beams from batches 1-3 were tested, one each, at ages of 7, 28, and 90 days; all specimens from batch 4 were tested at 365 days. The concrete with type II cement was used to make four beams; two were tested at 28, and two at 90 days age.

Characteristics of concrete

9. All the concrete had excellent workability, plasticity, cohesiveness, and finishing qualities.

Test results

10. Results of flexural and compressive strength tests were as follows:

	Type I Cement, Days Age				Type IS Cement, Days Age				Type II Cement, Days Age	
	7	28	90	365	7	28	90	365	28	90
Flexural Strength, psi										
	460	575	675	740	425	620	665	795	575	720
	445	530	675	690	385	595	710	605*	570	655
	490	575	560	700	430	600	715	765	660	655
	425	590	650	675	445	640	700	700	625	690
	530	550	585	695	455	610	700	825	--	--
	515	600	710	665	430	655	685	840	--	--
Average	480	570	640	695	430	620	695	785	610	680
Maximum	530	600	710	740	455	655	715	840	660	720
Minimum	425	530	560	665	385	595	665	700	570	655
Standard deviation, psi	41	25	58	26	24	23	18	56	--	--
Coefficient of variation, %	8.5	4.4	9.1	3.7	5.6	3.7	2.6	7.1	--	--
Compressive Strength, psi										
	3140	4610	5330	5830	2030	3630	4750	6500		
	3070	4240	4940	5660	2120	3750	4850	4800*		
	3130	4200	5160	4750*	1870	4060	5180	5850		
Average	3110	4350	5140	5750	2010	3810	4930	6180		

* Excluded from average

Resistance to Accelerated Laboratory Freezing and Thawing

11. Concrete mixtures were made with the type I and type IS cements and the aggregate combination used in the mixtures for strength tests, and also using the type IS cement with another aggregate combination: crushed limestone from a quarry in Kansas, and natural sand from the Kaw River, Kansas. Nine specimens were made from each mixture. The test results were:

Type I Cement Minnesota Fine Aggregate North Dakota Coarse Aggregate		Type IS Cement Minnesota Fine Aggregate North Dakota Coarse Aggregate		Type IS Cement Kaw River Fine Aggregate Kansas Limestone Coarse Aggregate	
Air, %*	DFE_{300}	Air, %*	DFE_{300}	Air, %*	DFE_{300}
4.1	76	4.3	86	4.3	34
3.6	72	4.4	94	4.9	39
3.9	70	4.2	95	4.7	40
4.5	77	4.4	90	4.0	38
4.3	79	4.2	96	3.9	34
3.7	73	4.2	94	3.9	32
3.8	74	4.6	93	4.5	40
3.9	76	4.4	93	4.3	37
3.5	58	4.2	95	3.9	40
3.9	73	4.3	93	4.3	37**

* Calculated by displacement of water by specimen.
** Average of 22 previous tests of this aggregate combination = 17, range 10 to 28.

Alkali-Aggregate Reaction Expansion

12. Mortar bars were made with the portland blast-furnace slag cement and with a reference low-alkali portland cement (Na_2O equivalent = 0.37%) using sand from the Right Terrace, Garrison Dam (SW 1/4, Sec 29, T 147 N, R 84 W, Mercer Co., North Dakota and tested in accordance with CRD-C 123. After 1-yr exposure neither group of mortar bars showed any measurable warping and the average expansions were 0.040 percent for those with the reference low-alkali portland cement, and 0.031 percent for the portland blast-furnace slag cement. The bars with the reference low-alkali portland cement showed very slight exudations of gel consisting of two or three small round spots per bar; those with the portland blast-furnace slag cement showed no such spots.

Color of Concrete

13 The surfaces of the concrete made using the type IS cement were light in color as was the dry cement and the freshly mixed concrete.

Broken concrete surfaces were very dark, almost black; the darkening apparently developed within 48 hr after mixing, and intensified with continued moist-curing until 28 days age. The color at 28 days age was nearly coal black, with a trace of blue and green. Upon drying the color lightened to the usual "concrete gray" for normal periods of moist-curing. Once dried, the color did not darken again on resumption of moist-curing.

Summary and Conclusions

14. The flexural strength of the type IS cement concrete exceeded that of the type I cement concrete at all ages greater than 7 days, and slightly exceeded that of the type II cement concrete at the two ages at which the latter was tested, 28 and 90 days. The strength gain of the type IS cement concrete was much greater than that of type I between 7 and 28 days, but not much different thereafter. The strength of concrete made with type IS was as great at 90 days as was that made with type I at 1 yr.

15. The compressive strength of the type IS cement concrete was lower than that of the type I cement concrete at all ages less than 1 yr. The type IS cement concrete consistently showed a greater rate of strength gain than the type I cement concrete.

16. The type IS cement with 0.25 percent Na_2O equivalent produced less evidence of alkali-aggregate reaction and expansion than the reference low-alkali portland cement.

17. Concrete made with the type IS cement showed greater resistance to accelerated laboratory freezing and thawing than comparable concrete with similar aggregates and type I cement. The tests using another aggregate combination also showed a greater resistance to freezing and thawing when the type IS cement was used than in previous tests with portland cement.

18. Except for usual precautions necessary when different brands of cement are used on a single job, color should prove no barrier to the use of type IS cement, except possibly in conspicuous architectural concrete.